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Land-Related Global Habitability Science Issues

Land-Related Global Habitability
Sciences Working Group

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Scientific and Technical Information Branch

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LAND-RELATED GLOBAL HABITABILITY SCIENCE ISSUES

CONTENTS

LIST OF FIGURES

LIST OF TABLES

ACRONYMS

AET	Actual Evapotranspiration
AgRISTARS	Agriculture and Resources Inventory Surveys Through Aerospace Remote Sensing
AIS	Airborne Imaging Spectrometer
APR	Automatic Profile Recorder
ARC	Ames Research Center (NASA)
AVHRR	Advanced Very High Resolution Radiometer
DBMS	Data Base Management System
DEM	Digital Elevation Model
DLG	Digital Line Graph
DMA	Defense Mapping Agency
DOC	Department of Commerce
DOD	Department of Defense
ET	Evapotranspiration
FAO	Food and Agriculture Organization (UN)
GEMS	Global Environmental Monitoring System of UNEP
GIS	Geographic Information System
GOES	Geostationary Operational Environmental Satellite
GSFC	Goddard Space Flight Center (NASA)
HCMM	Heat Capacity Mapping Mission
IBP	International Biological Program
ICSU	International Council of Scientific Unions
IFOV	Instantaneous Field of View
IR	Infrared

JSC	Johnson Space Center (NASA)
LACIE	Large Area Crop Inventory Experiment
LAI	Leaf Area Index
Landsat	Land Satellite
LFC	Large Format Camera
LIDAR	Light Detection and Ranging
LOS	Land Observations Satellite (Japan)
Metsat	Meteorological Satellite
MLA	Multi-linear Array
MSS	Multispectral Scanner System
NAS	National Academy of Sciences
NASA	National Aeronautics and Space Administration
NOAA	National Oceanic and Atmospheric Administration
NPP	Net Primary Productivity
SAR	Synthetic Aparture Radar
Seasat	Sea Satellite
SIR	Shuttle Imaging Radar
SPOT	Satellite Probatoire d'Observation de la Terre (France)
TBA	Total Biomass Accumulations
TIMS	Thermal Infrared Imaging System
TIROS	Television Infrared Observation Satellite
TM	Thematic Mapper
UNEP	United Nations Environmental Program
UNESCO	United Nations Educational, Scientific, and Cultural Organization

USDA	United States Department of Agriculture
USDI	United States Department of the Interior
USSR	Union of Soviet Socialist Republics
WMO	World Meteorological Organization

PREFACE

The scientific issues that underlie the land-related portion of NASA's part of a Global Habitability Program are described in this report. A companion volume describes the implementation plan for a program to address these issues. This scientific rationale and plan of action could form the basis of a "stand-alone" global research program which would greatly enhance our understanding of the Earth, its life and life support systems. The broader intention, however, is first to integrate this plan with other approaches being taken by NASA in developing a complete NASA Program: the Global Biology Program from the Division of Life Sciences, and the oceans and atmosphere portion from the Division of Earth Science and Applications. Second, the scientific issues which are outlined here will clearly require the coordinated acquisition of remotely sensed and in situ data from all parts of the globe. This will require a framework of cooperation with domestic and international organizations and with other nations. Over the past year, NASA has been working with other organizations to develop a Global Habitability Program to provide this framework. Care must be taken to ensure that the framework is structured in a manner which is in harmony with the on-going and planned activities of the domestic and international community.

This document reviews the major land-related scientific questions that the Global Habitability Program must strive to answer, and outlines the reasons for their importance. It also presents measurement requirements and discusses supporting science issues such as remote sensing capabilities and special needs in information science that must be addressed in parallel with the basic science issues to accomplish the goals of the program. In addition, the characteristics of a proposed research information network are described. Such a network would provide the necessary management, storage and retrieval of observational and derived data to a broad community of earth and biological scientists.

This document was prepared by the Working Group for Land-Related Global Habitability Sciences, which is composed of the following individuals:

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Reply to Attn of: EE-8

JUL 12 1983

Dear Colleague:

Global Habitability is a new programmatic theme within the newly organized Earth Science and Applications Division of the Office of Space Science and Applications. The objective of this program is to investigate long-term physical, chemical, and biological trends and changes in the earth's environment, including its atmosphere, land masses, and oceans. The program will specifically investigate the effects of natural and human activities on the earth's environment by measuring and modeling important physical, chemical, and biological processes, and their interactions. The program will involve the acquisition and analysis of space and suborbital observations, land- and sea-based measurements, modeling and laboratory research, and supporting data management technologies over a ten-year or longer period of time.

The enclosed report, Land Related Global Habitability Science Issues, deals with the land element of the Global Habitability program. The document is the product of the Land-Related Global Habitability Science Working Group which was convened to formulate NASA's focus in the study of the biosphere and to identify the specific science issues relating to the land areas of the Earth. Its purpose is to inform interested individuals and organizations of the science issues rationale, selected scope and research strategy of this part of the Earth Science program.

For further information on this program, contact Mr. Alexander J. Tuyahov, (202) 755-3055.

Sincerely,

S. G. Tilford

S. G. Tilford, Director
Earth Science and
Applications Division

Enclosure

LAND-RELATED GLOBAL HABITABILITY SCIENCE ISSUES

Executive Summary

In studying and understanding any portion of the biosphere, whether it be solid or liquid, we must examine its ability to partition its energy and mass to its surroundings. Therefore, the scientific areas of interest are energy balance, hydrology, biogeochemistry, and biological productivity, although there is considerable overlap among these science areas. For example, water plays an important role in all of them. It is paramount, therefore, that we understand all aspects of these science areas. This becomes even more apparent when we study transport processes on a global scale. It is in this opportunity to examine and predict changes on a global basis that we must determine the quantity and quality of the various land surfaces.

It is in the area of biological productivity that we can make a significant scientific contribution. We do not know with any acceptable degree of accuracy, the productivity of various biomes and the response of these biomes to environmental changes.

Paramount to global habitability is the biological productivity of the land. Productivity is the change in biomass with time. As biomass changes, so does the global energy balance, and the biogeochemical and hydrological cycles. Thus, any interest in energy balance, biogeochemical cycles or the hydrologic cycle must take into account the effects of biological productivity. The concern with biological productivity also makes special reference to agriculture and to the production of other renewable resources upon which people depend for food, shelter, fuel, and clothing.

This will be the first study of terrestrial biological activity on a global scale. It will involve a significant interdisciplinary approach with inputs from the physical, biological, and engineering sciences. An innovative coupling of "state of the art" techniques is envisioned, utilizing remote sensing, computer simulation modeling, and terrestrial ecosystem analysis. The program calls for five science elements: Global Energy Balance, Global Hydrologic Cycle, Biogeochemical Cycles, Biological Productivity, and Land Surface Inventory, Monitoring, and Modeling (see Figure ES-1). The Science Working Group approached the land-related global habitability problem by separating the biospheric phenomenon into five science elements. While these are not independent, they provide a convenient structure for identifying the science issues important for quality of life on Earth. They also provide a reasonable structure for implementing a future research program. The order in which these science elements are presented is not intended to convey any priority order.

Global energy balance, the biological productivity of the land, and the global hydrologic and climatic cycles are strongly interactive, and prime determinants of the land environment. It is not possible to understand one of these determinants well without understanding them all.

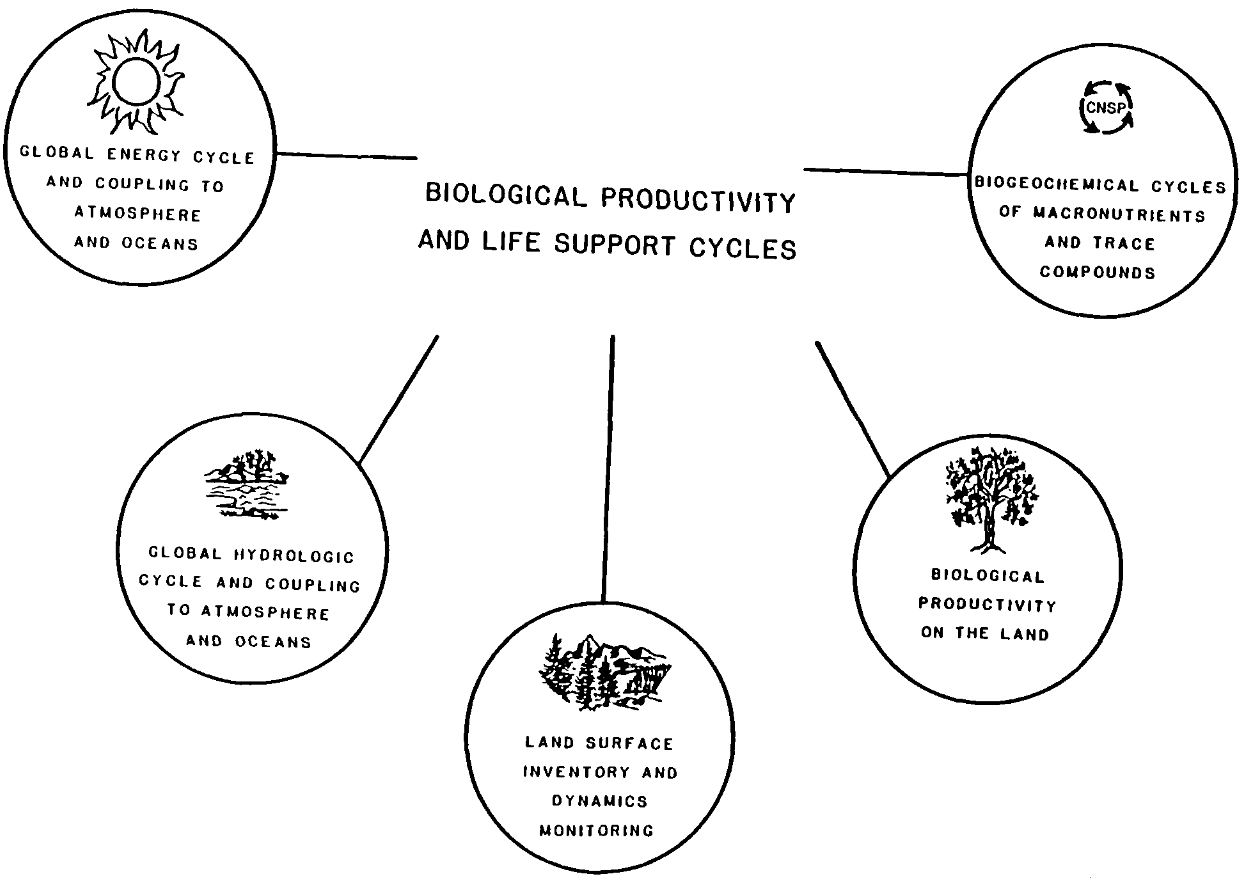

Figure ES-1 Science Elements in Land-Related Global Habitability

Global Energy Balance. A better understanding of the land component of the global energy balance should begin with an empirical estimate of land energy balance based on current models and data, including remotely sensed data. It should progress to the demonstration that remotely sensed electromagnetic measurements can provide repetitive global inputs. These are essential to the development of advanced energy budget simulation models needed for surface temperatures, for primary productivity, and as a driver for the hydrologic cycle. The research should culminate in experimentally proven and theoretically sound energy budget simulation models.

The energy balance of a surface describes the partitioning of energy by that surface and the energy coupling of the atmosphere to the surface. It is the energy and mass transfer at this interface that we seek to understand and quantify. Because the quantity and quality of vegetation both depend upon and singularly affect the energy budget, knowledge of the relations between energy balance and biological productivity is of particular importance. For example, the amount of vegetation present predominantly determines the relative magnitude of the latent heat flux. This flux is a major consideration in the hydrologic cycle, which determines available soil moisture. The amount of soil moisture available, in concert with other variables, determines biological productivity. The amount of absorbed solar radiation converted to latent heat also affects atmospheric processes contributing to atmospheric circulation patterns, which in turn affect the geographic distribution of biological productivity. Pursuit of the global energy balance sciences issues will increase our limited knowledge of such land/atmosphere interactions.

Science issues (research objectives) are as follows:

1. Establish the relationship between the land energy balance and land biophysical conditions.

2. Evaluate current spatial and temporal patterns of land biophysical conditions which affect energy balance.

3. Develop methods by which remotely sensed observations may be used to infer the land-air energy balance and the biophysical characteristics that affect energy balance.

Global Hydrological Cycles. The distribution of rainfall, evaporation, and runoff affect the amount and distribution of biomass and biological productivity. Changes in land cover and in biological productivity, in turn, can affect the hydrologic cycle locally, regionally, and globally. Of all resource inputs into the biological productivity of the land, water is perhaps the most critical and is becoming increasingly short in supply. The interaction of hydrology and global habitability occurs through the local availability of stored water and the runoff of excess water. Stored water supports and limits the growth of living systems. Through its evaporation, water exerts thermostatic control over local air temperature. Water runoff is an agent for the entrainment and transportation of sediments and nutrients and couples the land with the oceans. The crucial hydrologic issues center on an understanding of the coupling of the hydrologic cycle with atmospheric circulation. The proposed research program will develop this understanding

through physically-based mathematical modeling which includes the presence of vegetation, and will be supported by a program of field observations. The proposed science issues consist of the following:

1. Development of the knowledge base for short-term prediction of the local availability, movement, and quality of water, including snow and ice. The availability of water for primary productivity will be emphasized. This will include both data collection and modeling.

2. Understanding the cause and effect relations between land surface change and hydrologic change. This modeling task will address regional or continental environmental alterations on the seasonal and annual time scale.

3. Monitoring the global distributions of decadal change in the volume of stored fresh water above and below ground. This is a continuing data collection and analysis task directed toward statistical discrimination of long-term hyrologic change.

Biogeochemical Cycles. A key component in understanding the Earth as a living planet is the cycling of its constituent elements. These elements are continually incorporated into living biomass by the metabolic reactions energized by sunlight. To maintain the biosphere, these combined elements, principally carbon, nitrogen, sulfur, phosphorous and certain trace elements must be continually recycled or the evolutionary process will cease.

The processes by which the combined elements are released involves microbes which reside in the soils and sediments. Some elements such as carbon, sulfur, and nitrogen are returned to the atmosphere in gaseous forms: CO(2), CH(4), H(2)S, {CH(3)(2)S)), N(2), NH(3), etc. and are thus generally distributed. Others like phosphorous and certain trace elements are rendered soluble by microbial activity for use locally or transport by running water to other areas.

The proposed research would first generate new quantitative measures of the critical microbial activities in soils and sediments that can be sensed locally and the data transmitted to satellites. Specific test areas where coordinated studies of energy, hydrology, and above-ground plant activity can be coordinated to the below-ground (root) activity which profoundly effects the soil and sedimentary microbial activity would be instrumented. Data from these instrumented sites will then be coordinated with satellite sensed parameters to provide spatial and temporal insight into the global extent of these processes. Satellite observations are of particular importance as the most profound effects on the biogeochemical cycles are often the results of unusual events such as floods, fires, severe storms, etc.

Research Tasks will have the following objectives:

1. Develop quantitative measures of the critical microbial biogeochemical processes to be transmitted from instrumented sites that describe the dynamics of the major element cycles.

2. Evaluate interactions and couplings among the major element cycles,

their normal ratios and shifts from disturbance.

3. Determine the role of biota and microclimate linkages in controlling (stabilizing) element cycles.

4. Describe the dynamics of trace elements associated with major elements.

5. Identify the indicators of change in global element cycles.

Biological Productivity. Life on the land has major influences on the Earth's energy balance and biogeochemical cycles. Conversely, changes in biomass are driven by complex interactions among energy, water, element cycles, and the biota. Additionally the food, fiber and fuel consumed by modern society are derived primarily from terrestrial primary production. Thus, any study of the biosphere must include a study of the amount of and changes in biomass. Five science issues are recommended for the study of biomass and biological productivity (the change in biomass per unit time and area).

1. Assess the areal extent and spatial distribution of current biomass and productivity of the major biomes (a biome is a major class of ecosystems, i.e., coniferous forest, grassland, etc.).

2. Improve the accuracy of estimates of structural variables, total biomass, and net primary productivity of terrestrial vegetation and relate to environmental variables.

3. Establish the potential biological productivity and the abiotic factors controlling this potential productivity.

4. Establish the rates of decomposition of biomass and determine the factors controlling these rates.

5. Determine the extent to which changes (both positive and negative) could be initiated in the productivity of major biomes.

Land Surface Assessments. The ability to accurately classify and quantify land surface features from satellite and ancillary data must be dramatically improved. Accurate surface feature information is central to and supportive of all land related research. A central focus of the research proposed is a determination of those factors which influence the long term ability of the land to support given levels of biological productivity and/or sustain elemental cycles.

A basic need identified in the land surface program element is the implementation of research on a set of classification systems for which information on land capability and other habitability parameters may be based. Other major needs addressed include research directed towards: the identification of major vegetation types, their areal extent, and distributions; and, the nature, extent, and frequency of surface disturbance from natural and anthropogenic sources. Specific research addressed include the development and improvement of:

1. A set of hierarchical surface cover classification schemes to support global habitability research.

2. Global surface cover inventory and monitoring techniques directed towards understanding factors which impact land capability.

3. Models for assisting in the determination of surface features and their temporal dynamics.

4. Appropriate sampling strategies for combining and extrapolating detailed site-specific information to global estimates.

5. Processing algorithms and methodologies for extracting land surface information from remotely sensed data.

6. Techniques for integrating and processing of data obtained from satellite and aircraft remote sensing with other data types within a geo-referenced data base.

Throughout this report, the basic science issues and the research needed to address them have shown a unique dependency upon information systems. All efforts discussed involve data collection, reduction, analysis and presentation. Thus, it is appropriate that the information systems needs required to support the research described herein receive a focus comparable with the science programs themselves.

Measurements of variables influencing global habitability pose two scientific challenges. First, though some variables are routinely measured today, others will require active development of scientific instruments and techniques. Second, spatial and temporal measurement sampling strategies that accurately support knowledge requirements while avoiding data floods and seldom-used archives require thoughtful development.

The uniqueness of the research objectives in each science element is a result of (1) the global perspective of the research (this is the first study of biological productivity on a global scale), (2) the synthesis of energy, water, biogeochemistry, and biological productivity, and (3) the mix of disciplines and technical capabilities planned.

The above science issues associated with the five science elements, along with the associated measurements and information science, if pursued, will constitute a long-term commitment not only by NASA and other agencies national and international, but it will also require the collaborative efforts of scientists from many disciplines and from all nations. This opportunity and this challenge for science are unprecedented in the history of the Earth.

LAND-RELATED GLOBAL HABITABILITY SCIENCE ISSUES

I. INTRODUCTION

The science of global habitability had its origin in the concept that the earth is one huge life supporting system made up of discrete parts working together. The workability of these parts (land, oceans, atmospheres, global biology), however, is not clearly understood and humanity is subtly and surely introducing changes and interfering with the balance of components within them. During the last half of the 20th century, human beings have been changing the nature of the earth's land, atmosphere, and oceans. The impact of modern technology on the biosphere is evident worldwide. Human activities, fueled by increasing numbers of people and their demands for goods and services, are affecting the biosphere through changes in land cover and biological productivity, the global energy balance, soil moisture and ground water reserves, the biogeochemical cycles, atmospheric CO_2 and in trace compounds including pollutants and toxic substances in the environment (SCEP, 1970; Holgate, et al., 1982).

It has become clear that there is a complex interplay between the living and non-living components on the earth. On the land, life depends on the earth's oceans, atmosphere, and sediments. Their characteristics are peculiarly suitable for life. On the other hand, life greatly influences the characteristics of the earth's surfaces. Every characteristic of our planetary surface has been strongly changed by the presence of life. These characteristics affect the energy and mass balances and biogeochemical cycles; from the qualities that affect energy exchange -- absorption, transmission, reflection -- to atmospheric and oceanic chemistry, to the characteristics of sediments and minerals. This global interplay between life and the environment is the focus for a new science -- a science of the biosphere (Hutchinson, 1970).

The study of the biosphere is one of the major scientific challenges of the next decade and is essential to our survival. Technological capabilities achieved during the past decade coupled with this new scientific view mean that for the first time a truly global understanding is within our grasp. Land remote sensing from satellites, which NASA has developed with information extraction techniques, provides new tools for global measurement and monitoring of changes in the biosphere. Computer and telecommunication advances within the last five years have dramatically increased the capability to handle and analyze global data bases. Of paramount importance are new theoretical models that provide direction and focus for future data acquisition and research while reflecting current understanding.

The global character of the study of the biosphere demands the snyoptic, repetitive space capability to observe and measure aspects of the earth which only NASA has developed. It also demands recently developed computer and telecommunication capabilities. NASA has no operational, service, or regulatory responsibilities. Part of NASA's charter is to pursue difficult research programs unimpeded by short-term requirements. In carrying out its mandated responsibilities in space science and applications, NASA has learned how to work with the total science community. NASA has had experience with

large, interdisciplinary project management required for this research. The intent of these Land-Related Global Habitability Science Issues (objectives), if pursued, is to provide the United States and the world with a significantly improved knowledge base.

This NASA initiative on global habitability focuses on time and spatial scales that encompass several scientific issues relating to changes on the earth's land masses. The crucial issues involve large scale changes that will affect man's primary needs: food, water, and suitable climate. Of major importance is the relationship between the land (including all life on the land) and the global climate system, and possible changes in the relationships resulting from changes in atmospheric gases, albedo, and moisture. Another area of importance is the complex response of the land and its life to atmospheric and oceanic changes. Because people inhabit the land surface, these changes cannot be separated from the overall global habitability study, nor would such a separation be in the interest of a valid scientific study of "habitability" on a global scale.

The science issues which follow concern a study of the structure and processes of the biosphere as they are influenced by land surfaces. The program emphasizes the spatial and temporal aspects of biospheric dynamics of both anthropogenic and natural origins. Attention is also given to the global energy balance and the hydrologic cycle. Changes in the biogeochemical cycles, including increases in atmospheric CO_2, and changes in the trace compounds in air, land, and water are considered. There is a focus on specific changes on the land surface and in biological productivity. The center point of all these changes is on human well-being and biological productivity (Figure ES-1).

Global Energy Balance. Science issues herein are designed to improve understanding of the role of energy balance at the land-air and land-water interfaces in global land biological productivity, hydrology, climate, and geochemistry. All interact in the biosphere through the driving force of solar irradiation. Changes of state of water depend on energy balance, which in turn depends on water state. The resulting hydrology and geochemical transport by rivers alters rocks and soils, inducing or inhibiting vegetation growth. Vegetation affects hydrology and soil biochemistry and dramatically alters energy balance through absorption by optical trapping and transpiration. It is not possible to understand any single factor of global habitability by itself. Each is a part of an interacting system with feedback, energy storage and conversion, transport lags, and the other complexities that arise from total system characteristics.

Hydrologic Cycle. There is an intimate linkage between the hydrologic cycle and biological productivity. This is illustrated by the soil moisture and subsurface water supply processes. Soil moisture is a driving variable for all vegetative growth and therefore for changes in biomass and in biogeochemical cycles, both through its supply of essential water, and through its regulation of surface temperature. Vegetation, in turn, influences soil moisture and the hydrologic cycle. Variations in soil moisture affect the production of all land biomass, including agricultural crops. For example, soil moisture in the spring is the most critical factor for agricultural

productivity in the U.S. corn and wheat belts. The current overdraft of ground water in the U.S., mostly for crop irrigation, is estimated at 20-25 million acre feet/year. This is a largely irreversible use of a generally non-renewable resource that will not only impact future agricultural productivity but also is currently causing land subsidence affecting human habitation in some valleys of the western United States. The problem of fresh water resource depletion and recognition of the importance of fresh water as a resource for human habitation is not restricted to the U.S. Agriculture is the major consumer (80-85%) of fresh water. Many forested watersheds provide major sources of water supply for human use. Deforestation has major effects on these sources, tending to increase the variability in supply, changing the subsurface storage and the surface runoffs. The kind of land cover can have regional and global effects on the hydrologic cycle. Water, because of its effects on biological productivity, will likely become the most limiting of all resources for future global habitability.

Biogeochemical Cycles. The global element cycles (nitrogen, carbon, sulfur, phosphorus) are inescapably coupled with the earth's energy balance and hydrologic cycle. The biogeochemical element cycles support biological productivity on land but at the same time are maintained in large part by functions of plants and organisms. The assimilation of carbon from the atmosphere by photosynthesis, incorporation by consumer organisms, and release back to the atmosphere by decomposition is the fundamental pathway for material cycling through terrestrial ecosystems. Assimilation by photosynthesis is driven by solar energy, and water is a primary constituent of this biological process. Human society is now inadvertently conducting a great biological-environmental experiment, the outcome of which is not known. Atmospheric CO_2 is increasing at the rate of 2 parts/million/year (Keeling, et al., 1976). This is attributed primarily to the combustion of fossil fuels and to deforestation. Most attention to this phenomenon has thus far been directed toward climate change which might increase global temperatures, raise sea levels, and melt ice caps. Some major agricultural dislocations and disruptions in food supplies might occur as a result of rising temperatures and shifts in precipitation patterns. The direct effects of increasing atmospheric CO_2 concentrations on net primary productivity may also be substantial and demands critical observation and analysis.

Biological Productivity. In the most literal sense, global habitability is defined by global biological productivity. Analysis of global productivity, and long-term changes in productivity, provides the best measure of whether global habitability is being irreversibly altered. Yet, classical concepts of ecology cannot even be addressed for the global ecosystem. Is the global ecosystem stable? How are the ecosystem characteristics controlled by the physical environment of energy, water, and elemental cycles? Do the biota modify these cycles significantly? What is the resiliency of the global ecosystem to perturbation (acid rain, CO_2 buildup, volcanic dust clouds)? The objective of the biological productivity section is to develop a scenario for studying the rates and controls of terrestrial productivity at a global scale. To answer these questions at a global scale, a necessarily mechanistic view of the structure and function is proposed. Beyond broad categorization of biomes(forest, grassland, desert), the focus will be on plant-related processes that conduct energy and material exchange, rather than species groupings.

Land Surface Assessments. Changes in land surface and biological productivity can have global effects. These changes include deforestation, reforestation, desertification, desert reclamation, soil erosion, overgrazing, excessive tillage, the ever-increasing area of irrigated agriculture, and soil problems that arise from salinization, a lack of drainage, and toxic metal accumulations. Neither the magnitude nor the rate of any of these changes is known, yet volumes have been published as to the future hazards of some of the above practices and phenomena on our planetary life supporting systems.

For each of the five science elements above, the more important measurements (observations) needed to address a particular science issue are considered. Since it is clear that any complete enumeration of measurement requirements by each of the five elements would result in considerable duplication in the document, no attempt was made to do so. In a succeeding iteration leading to a more complete program description, identification of the measurement requirements for each science element needs to be developed. Considerable savings could accrue from integrating these separate needs into a common set of requirements.

The measurements programs required to support the land-related global habitability science issues range from local site, off-the-shelf, well-established monitoring instruments and procedures to the global field, aircraft, and satellite-based techniques developed in earth sciences and remote sensing within the past decade. There is a large diversity of measurement variables: temperature, moisture content, nutrient concentrations, leaf numbers, areas, and angular distributions, radiance fields, species identification and well-being, land cover types, humidity, evapotranspiration, soil composition, rainfall, and wind velocity, just to name a few. Experiences of the last decade indicate that while many of the natural variables are routinely measured in situ, others (some that appear the simplest) are most challenging. Leaf area index, leaf geometric distribution, and average leaf number per plant are conceptually easy to perceive, but difficult to measure well and consistently, even in a single place at a single time. Certain of the variable measurements stated as needed by earth scientists may prove infeasible and require, instead, indirect, more feasible measurements followed by a well-reasoned chain of model-based inference.

The need to measure, over wide areas and frequent time intervals, the spatial and temporal dynamism of land surface and its atmosphere is a challenge which is a science and technology issue in itself. The remote sensing experiences of the last two decades point up both the difficulty and the necessity of wide area, frequent measurements to build true global knowledge of the biosphere and its phenomena. Spatial and temporal sampling strategies and information systems that accurately support knowledge requirements while avoiding data floods and seldom-used archives remain pivotal challenges of a global measurement system.

II. SCIENCE ISSUES

"Science is built up with facts, as a house is with stones,
But, a collection of facts is no more a science than a
heap of stones is a house." Poincare (1909)

In this section, the major science issues selected for study, which are also called science elements, are described for the Land-Related Global Habitability Program as are the aspects of understanding the program plans to achieve in the first ten years. Emphasis, however, is placed on the first five years. Research areas and measurement requirements associated with each issue are also discussed. Supporting science issues in measurements and information extraction are discussed in the next section.

There are five major science elements in the Land-Related Global Habitability Program:

1. Global energy balance and coupling to atmosphere and oceans
2. Global hydrologic cycle and coupling to atmosphere and oceans
3. Biogeochemical cycles of macronutrients and trace compounds
4. Biological productivity of the land
5. Land surface inventory, monitoring and modeling.

II.1 GLOBAL ENERGY BALANCE AND COUPLING TO ATMOSPHERE AND OCEANS

II.1.1 INTRODUCTION

The objective of this part of the program is to improve understanding of energy balance at the land-air and land-water interfaces and its role in global land biological productivity, hydrology, climate, and geochemistry. All of these factors interact in the biosphere through the fundamental driving force of solar radiation. Changes of state of water depend on energy balance, which in turn depends on water state. The resulting hydrology and geochemical transport by rivers alters rocks and soils, inducing or inhibiting vegetation growth. Vegetation presence affects hydrology and soil biochemistry and dramatically alters energy balance through absorption by optical trapping and transpiration. It is not possible to understand any single factor of global habitability by itself, but only as part of an interacting system with feedback, energy storage and conversion, transport lags, and the complexities that arise from these basic system characteristics.

The energy balance of a surface can be described as:

$$R(i) - R(o) = ET + H + G + P + F \qquad (1)$$

where R(i) and R(o) are the incoming and outgoing radiation streams and the difference represents the net radiation; ET is the evapotranspiration; H is the sensible heat to or from the atmosphere; G is the heat storage term; P is the photochemical term; and F is the horizontal transfer of energy

(advection). The left-hand side of equation (1) represents the radiant energy supply. The quantity and quality of the incoming radiation R(i), is dependent upon the incoming solar radiation, the turbidity, and the gaseous constituents of the atmosphere. The outgoing radiation, R(o), is dependent upon the bidirectional reflectance, emissivity and temperature of the surface. For example, R(o) for a bare soil would differ over much of the spectrum from that of a grass cover. R(o) is also an input to atmospheric radiation balance. Components of R(o), including reflected solar radiation and thermal emissions, are observed by remote sensing devices, modified by altitude-dependent atmospheric scattering and absorption.

Evapotranspiration depends on physical and physiological processes and is the latent heat transfer from soil, plants, and water surfaces. About 70 percent of the precipitation falling on the land surface is evaporated. The transfer of water in the plant-atmosphere system is a change of phase from liquid to vapor within the leaf; water vapor transport to air is a diffusion process through pores (stomata) whose openings are regulated by the plant. The stomata usually close during periods of darkness and low soil moisture with a resultant decrease in the diffusion of water vapor (transpiration) from the leaves.

Sensible heat, H, is the vertical component of heat transfer between the surface and ambient air stream by molecular conduction and convection and is strongly influenced by wind or convection current velocities. The amount of heat stored, G, is dependent upon the thermal properties of the surface and subsurface. Because a surface does not continue to cool or heat, G averaged over time scales measured in years is very nearly zero. The formation of glaciers and ice caps and the heating of soil in spring are examples of net loss or gain in G over lesser time spans.

Photosynthesis, P, is the photon energy flux used in conversion of carbon dioxide and water by green plants into carbohydrates. Only 3 percent of the incoming solar energy is used in photosynthesis, but this small energy term is the important basis for biological productivity. Transpiration and photosynthesis are inextricably linked because the diffusion of carbon dioxide from the atmosphere to the leaf interior for photosynthesis is through the same pores (stomata) that water vapor passes to the atmosphere; therefore, the carbon and water cycles are interwoven with the energy cycle.

While the previous energy balance terms are primarily vertical and one-dimensional, the advection term, F, represents the horizontal transfer of energy. On a micrometeorological scale, wind blowing across a fallow field onto an irrigated corn field represents a horizontal transfer of heat to the corn plants which will increase their rate of evapotranspiration. Advection can also occur through subsurface heat transfer and mass transport.

Budyko (1974) presented the annual mean components of the earth's energy balance as a function of latitude. On a yearly basis, the oceans have a significantly different energy balance than land. Evapotranspiration is the largest mean component for both oceans and land. The advection term for oceans can be sizeable because of heat transport by ocean currents. Variation with latitude of evapotranspiration and sensible heat for land areas are due

to changes in precipitation patterns and resultant vegetation cover variation. Dense vegetation cover increases evapotranspiration and decreases sensible heat when compared with sparse vegetation cover.

Figure 1, adapted from Sellers (1965), presents a schematic representation of annual and diurnal variations in energy balance components at selected sites in the United States. Stored energy in the annual regime is less than 10 percent of the budget and is not shown. The most significant regional differences occur in the relative magnitudes of sensible and latent heat fluxes. Again, these differences are qualitatively related to the amount of vegetation present; a site with more vegetation shows a large portion of the energy budget consumed in evapotranspiration processes. This partitioning of the energy balance is not only an indicator of the biological productivity of the site but also is descriptive of the local microclimate which determines the boundary conditions for atmospheric energetics, contributing to regional climate patterns.

Assessment of regional variations in the factors that determine the land energy balance is critical to evaluation of the interactions between land conditions, climate, hydrology, and global productivity. Charney (1975) proposes that an increase in surface albedo, as a result of vegetation removal in the Sahel region of Africa, will alter regional rainfall patterns due to positive feedback effects in the energy budget. In areas where rainfall is suppressed by this change, further reduction in vegetation cover will occur through reduced availability of the moisture needed for survival and growth of vegetation.

The rate of diffusion of carbon dioxide and water vapor to and from plant organs is controlled by the stomata/openings which are in turn regulated by the water balance of the organ (in most cases, plant leaves). Therefore, the availability of water and the plant's ability to extract water from the soil water reservoir strongly influences transpiration and photosynthesis. The availability of soil water is not only dependent upon the soil hydrologic properties but also the plant's ability to grow roots for improved extraction. In turn, root growth is dependent upon the stage of growth of the plant. Limited soil water supply caused by lack of precipitation or high evaporative demand can result in decreased photosynthesis. Subsequently, leaf growth is reduced and abcession of leaves results; thereby, transpirational cooling is reduced and the plant increases in temperature. Concurrently, one usually observes an increase in soil temperature. This, in turn, increases the sensible heat to the atmosphere, and air temperature increases. The air mass then moves into the surrounding area and becomes a source of energy (and possibly stress) for the adjacent ecosystem. In addition, the increase in soil temperature can affect biological activity as well as biogeochemical cycling. Therefore, a change in the energy balance of one ecosystem can impose significant environmental effects on another.

The factors that control the energy balance of the land include albedo, emissivity, thermal inertia, moisture availability, and surface roughness. These factors interact with atmospheric conditions to determine energy flux and balance. Albedo describes the percentage of incident solar radiation that is reflected in the visible, near, and shortwave infrared spectrum out to

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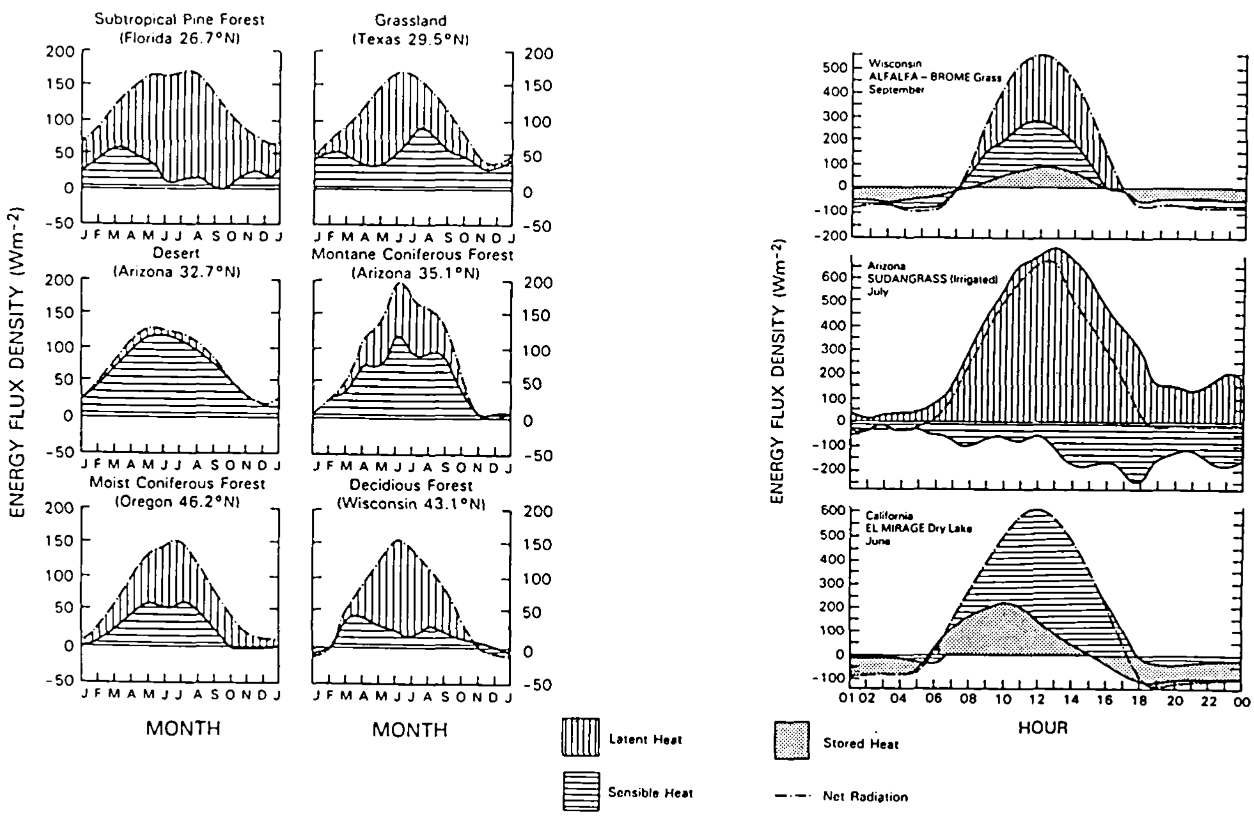

Figure 1 - Annual and Diurnal Variations in Energy Balance Components

about 3 to 4 um wavelength. Emissivity describes both the absorption and radiation of thermal infrared wavelengths at typical Earth temperatures, wavelengths ranging from 3 to 4 um to the far infrared at tens of micrometers. Albedo and emissivity together control the interface net radiation budget. Thermal inertia is an integrated expression of interface thermal properties (conductivity, specific heat, and density) that determines subsurface heat storage magnitude, which affects surface temperature, which in turn affects the sensible heat flux. Moisture availability describes the degree to which water is available for transpiration and evaporation. Since transpiration is a physiological as well as a physical process, basic physiological responses are important. These factors control the partitioning of the energy budget between evapotranspiration and other fluxes. Where water is not limited (and atmospheric humidity not saturated), evapotranspiration will dominate the energy balance. Surface roughness describes the turbulance effect land conditions have on advective flow of air. The greater the roughness, the greater the turbulance which enhances both sensible and latent heat fluxes.

Land albedo, emissivity, thermal inertia, moisture availability, and surface roughness are determined by the amount present, type and condition of vegetation, water, and soil (or rock or man-maoe material). Table 1 provides a qualitative overview of the relations between these land materials and the energy balance factors which they determine. A fully quantitative assessment of these relations, particularly as a function of the differential characteristics of various global biomes, is not currently available. The biophysical properties of vegetation which affect energy flows and balance, where known, show significant variations.

Oke (1978), for example, describes the comparative diurnal energy budgets of two coniferous forests observed under essentially identical conditions. Whereas, the net radiation budgets are quite similar, the Bowen ratios (sensible heat/latent heat) differ by a factor of three. The differences in partitioning the energy balance into sensible and latent heat are related to differences in stomatal behavior in the species that make up the two forests. Relations between the hemispherical albedo of vegetation and the structural and optical properties of the canopy are also not well known. Instrumentation and observational techniques are just becoming available that will allow measurements to be made to evaluate competing theories which purport to explain these relations. Similar limitations exist in many of the other relations shown in Table 1.

II.1.2 SCIENCE ISSUES AND THEIR IMPORTANCE

There is general understanding that land biological productivity is related to the amount of energy absorbed and the manner in which this energy is partitioned into various energy fluxes. Further, it is recognized that the land-air energy budget is largely determined by the biophysical characteristics of land. However, detailed quantitative knowledge of these relations, across the diversity of global land biophysical conditions, is poor. This is principally because of the difficulty in carrying out extensive field measurements which would capture the diversity of land biophysical conditions. Theoretical description of land-air energy budgets is well developed in the form of numerical models. However, it is impossible to validate the realism

S83-32957

LAND FACTORS	Vegetation		Water: Liquid		Water: Solid		Soils and Other (rock, man-made)	
	Relative Magnitude	Sources of Variability	Relative Magnitude	Sources of Variability	Relative Magnitude	Sources of Variability	Relative Magnitude	Sources of Variability
Albedo	low-moderate	o plant cover o canopy structure o phenology o leaf, stem and bark o stress	low-moderate	o turbidity o depth o bottom conditions o surface turbulence	high-moderate	o internal structure o grain size o surface contamination	moderate-low	o grain size o internal structure o minerals o organic matter o moisture
Emissivity	high	o generally high with exceptions (e.g., lemon tree leaves	high	o not known to vary significantly	high	o possibly lower for cold, small grained snow	high-low	o silicate content o dielectric properties (metals) o weathering o surface roughness
Thermal Inertia	low	o generally assumed near zero o thermal mass of canopy o phenology	high	o subsurface turbulence	moderate-low	o internal structure o density (ice-snow)	moderate-low	o grain size o internal structure o minerals o organic matter o moisture
Moisture	high-low	o root system o stomatal resistance o canopy structure o phenology	high	o not known to vary significantly	low	o temperature	moderate-low	o grain size o structure o profile o organic matter o moisture
Surface Roughness	moderate-high	o canopy height o canopy structure	low-moderate	o surface turbulence	low	o not known to vary significantly	low-high	o local relief o surface structure (urban)

TABLE 1 - Relations Between Land Materials and Energy Balance Factors

of the predicted patterns since the required inputs that describe land biophysical conditions are not well known, and too few observations of land energy budget patterns are available to test the validity of the predictions.

To solve the observation problem requires a methodology that is less constrained, spatially and temporally, than traditional field methods. Remotely sensed observations offer great promise in this regard. Key aspects of the land-air energy cycle are observed by remote sensing techniques. Current research suggests that both important land biophysical characteristics such as albedo, thermal inertia, and green leaf area index and components of the energy budget, such as evapotranspiration, may be inferred from remotely sensed observations. Significant scientific progress will be achieved in land energy budget research if methods are developed by which remotely sensed observations may be used to study the spatial and temporal patterns of land energy balance in relation to land biophysical conditions.

Specific scientific issues that must be addressed to meet the objectives of the global energy balance portion of the program include:

1. Establishment of the relations between the land energy balance and land biophysical conditions.

The dynamic relations between land conditions and energy balance must be known in order to model and study interactions between environmental conditions and global habitability. Within a given range of environmental conditions, as defined by the energy, hydrologic, and geochemical cycles, land biophysical conditions will tend to modulate the energy balance in a manner which maintains the biophysical conditions. When these environmental limits are exceeded, the land biophysical conditions change, altering the way they affect the energy balance. This, in turn, will further alter the environmental conditions until a new dynamic equilibrium is established between the land conditions and the energy, hydrology, and chemical cycles. Better understanding of the manner in which various land biophysical and physiological conditions modulate the energy balance is needed in order to understand the dynamics of the biosphere.

2. Evaluation of the current spatial and temporal patterns of land biophysical conditions which affect the energy balance.

Little is known about the current geographic distribution and temporal dynamics of land biophysical conditions. This is not surprising since, as noted in the land cover inventory portion of this program, there are serious shortcomings in knowledge of the distribution of basic land cover types. The two problems are related but not synonymous. The land biophysical conditions, including albedo, emissivity, thermal inertia, moisture availability, and surface roughness, are the integrated product of the amount, type, and condition of vegetation, water, and soil present, and can therefore not be simply specified by a generic regional cover type. Analysis of these patterns can only be accomplished through detailed analysis of remotely sensed observations. Knowledge of these patterns is essential since any effort to model the components of global habitability requires this input information.

3. Development of methods by which remotely sensed observations may be used to infer the land-air energy balance and the biophysical characteristics that affect energy balance.

The amount of solar radiation reflected and the longwave radiation emitted by land are directly observed using remote sensing techniques. These radiant fluxes are related to the amount of energy absorbed and the current state of the energy balance at the interface. Research over the last 20 years has shown the net radiation budget and other elements of the energy balance, particularly evapotranspiration, can be inferred from these measurements when used in conjunction with meteorological observations and energy balance models (Vonder Haar, and Suomi, 1969; Malila, and Wagner, 1972; Soer, 1980; Carlson, et al., 1981). Current research activities suggest that the amount of photosynthetically-active vegetation present (green LAI) can be inferred from transforms of visible and near infrared observations (Tucker, 1979; Wiegand, Richardson, and Kanemasu, 1979). Thermal inertia, soil moisture, and surface roughness also appear to be derivable from remotely sensed observations (HCMM, microwave, radar).

The knowledge and experience in the remote sensing community should be integrated to develop a systematic means to use remotely sensed observations to derive the land energy balance. This methodology will be the only effective means to study the complex patterns of land energy budgets.

II.1.3 RESEARCH AREAS

Research activities will simultaneously pursue analysis of global energy balance and land biophysical characteristics, integration of remote sensing techniques, and development of basic knowledge. Specific research activities are described below.

1. Produce an empirical estimate of land global energy through two related activities. First, collect available energy budget studies and models together with current land-cover studies and estimates of the biophysical characteristics for various land types, and analyze these findings. Second, archive and analyze global remotely sensed observations from a variety of platforms and sensors (AVHRR, Landsat, Seasat, HCMM, etc.) for global energy balance inferences. Finally, produce a best estimated global energy balance set of patterns over land masses.

2. Conduct experimental and theoretical research to develop analytical methods whereby multispectral electromagnetic sensing measurements may be used to infer energy fluxes and land biophysical characteristics. The experimental work should include ground measurements of energy and mass fluxes, physiological response, biophysical condition, and radiance patterns at selected sites coupled with aircraft and satellite observations when possible. The theoretical work should emphasize fundamental energy and mass transport theory applied to the complex geometries and constituents of the natural scene, subjected to the tests of the experimental effort on both qualitative and quantitative scales.

3. Develop advanced energy budget simulation models that explicitly

account for the biophysical characteristics of land. This will include inference of regional energy budgets from measurements of bidirectional hemispherical radiance patterns, apparent thermal inertia, moisture availability and surface roughness, and inference of the optical, thermal, physiological, and structural attributes of the land interface. The simulation models should have connecting links with other program elements to fit into a total land global habitability model.

II.1.4 MEASUREMENT REQUIREMENTS

More detailed measurements of specific sites are required to establish the hemispherical albedo, emissivity, thermal inertia, available moisture, and surface roughness of land as function of biophysical conditions. As an example, determination of the hemispherical albedo of the earth's surface requires measurement capabilities beyond those currently available. Micrometeorological measurements of wind, temperature, and humidity will be required for calculations of heat and mass fluxes. Detailed physiological measurements will also be required to quantify response functions. Pointable visible and near infrared radiometers are required. Experiments ranging from small-scale field experiments utilizing boom mounted devices and aircraft to regional (1000-10,000 square km) investigations from a Shuttle-based instrument, are required. The experiments should be conducted for areas representative of all land cover types. Temporal resolution will vary for the various cover types (every 3 days to 30 days). The capability to correct for atmospheric path radiance as a function of surface properties and atmospheric aerosol loading is required.

Low resolution data from the AVHRR in the visible, near infrared and thermal infrared should be acquired on a global basis, weekly, for two years, and on at least a monthly basis thereafter. Future systems with similar capability should include narrower bands to improve the discriminability of the system.

Landsat Thematic Mapper (TM) imagery, including thermal data, should be acquired for selected sites on a seasonal basis for the duration of the study. The feasibility of using nighttime thermal data to determine boundary conditions for thermal inertia and moisture availability should be explored.

Space-based bidirectional measurements should be made of selected sites in the visible, near infrared, and, where possible, thermal infrared. Concurrent atmospheric sounding to establish atmospheric optical properties is highly desirable. Similar measures of typical regions within various biomes are needed to provide estimates of the hemispherical albedo for areas with known cover types. Non-sun synchronous data is preferred; repetitive coverage of selected areas is more desirable than global coverage.

II.2. GLOBAL HYDROLOGIC CYCLE AND COUPLING TO ATMOSPHERE AND OCEANS

II.2.1 INTRODUCTION

Humans now have the technology to control their destiny by redefining hydrologic behavior on a continental scale. We can literally divert rivers across continents in order to alleviate shortages in areas that we believe to be critical. Perhaps the most significant effort in this area at present is the project being undertaken by the Russian government that will redirect the waters of five of its major rivers away from the Arctic Ocean toward the Caspian and Aral Seas almost two thousand miles to the south. Unfortunately, humans have not developed the scientific base necessary to understand the processes defining a region under its natural conditions, or to predict what the region will become if they intercede. As exemplified by the consequences of human intercedence in the regime of the Nile River, we need a better understanding of the behavior of continental ecosystems before we can confidently undertake such projects.

As the power of human technology continues to grow, there will be increasing opportunities and, indeed, increasing pressures to use it to produce massive change. Public works programs have been a vehicle for combating socio-economic problems since the dawn of history. The Tigris-Euphrates river diversions and the construction of the Egyptian pyramids initiated a strategy that has progressed through the public works programs of the 1930's to a proposed resurgence in road building activities in the immediate future. On the not too distant horizon are opportunities to undertake public works programs that could have the redistribution of water resources within a continent as their objective. Rather than considering such an undertaking to be frightening or to be the fantasies of a dreamer, they should be considered as an opportunity to, for the first time in human history, apply technology toward the noble goal of improving the quality of human life on a massive scale when it might otherwise move into a long-term period of economic uncertainty. These opportunities, however, are not available to us until we make a concerted effort to fill many critical gaps in scientific knowledge. Rather than having to react to what we consider uncontrollable events, an improved scientific base will allow humans to anticipate these events, make scientifically sound adjustments and, thereby, provide an improved quality of habitation on a global scale.

Global coverage by high quality remote sensing systems, coupled with the recently developed power to manage and interpret the resulting data through highly efficient geographic information systems, places us in a position to be able to develop a scientific understanding of hydrology that is consistent with the power of our technology to impose change. However, this understanding can only be developed through a well-coordinated, intensive program on a global scale. While detailed, regional-scale hydrologic analyses must be an integral part of the program, the extent of the interactions among processes controlling the quality of habitation requires that the effort be of global scale.

The objectives of the global hydrology effort will be to develop the necessary scientific base from which we can: (1) anticipate the hydrologic consequences of natural processes or human driven changes; and (2) design strategies for improving the quality of habitation on continental scales by imposing hydrologic change through the application of currently available technologies.

II.2.2 SCIENCE ISSUES AND THEIR IMPORTANCE

The fundamental scientific issue is understanding and formulating the dynamic coupling of the hydrologic cycle (see Figure 2) with the atmospheric circulation (Eagleson, 1982). This problem can be broken into three parts according to its characteristic space and time scales. In order of the immediacy of useful payback, these issues are:

1. Definition of the global distribution of the atmospheric forcings and physical parameters that enter into the prediction of soil moisture fluxes and the associated surface runoff (JPS, 1981). The emphasis is on local, short-term temporal variations, and will involve both data collection and the refinement of existing one-dimensional hydrologic models which generate soil moisture fluxes and runoff from given atmospheric inputs.

Precipitation is the major input and driving force in the hydrologic cycle while, at the same time, it is one of the major forcing functions in climate processes. Because of its inherent links with soil moisture and snow storage, precipitation is the critical element for agricultural production and domestic water supplies. An overabundance or marked deficiency of precipitation can have catastrophic consequences such as floods and droughts. Evapotranspiration is an important hydrologic process because approximately 70 percent of the precipitation falling on the land surface is returned to the atmosphere via this route where it is a source of subsequent precipitation. Evapotranspiration powers the atmospheric circulation through latent heat, it is vital to plant physiology, and it serves as a natural regulator of our surface temperature.

The moisture stored in the soil determines the partitioning of precipitation into runoff and infiltration components. The soil moisture also affects the partitioning of net solar radiation at the land-atmosphere interface. Finally, the soil moisture has a direct and dramatic effect upon the growth of vegetation and upon global food production.

The volume of water stored as snow affects forecasts of water supply and flooding, crop planting selection and strategy, irrigation, and management of agricultural commodities and surpluses. Additionally, because of the snow's high albedo and variable areal extent, its presence or absence can drastically alter the energy budget and surface temperature. Knowledge of the properties of snow is vital for improving medium- and long-range weather forecasts and for perfecting general circulation models.

The runoff of water toward and within streams is an agent for the entrainment, transportation, and ultimate deposition of sediments, anthropogenic chemicals, and nutrients both dissolved and absorbed. The structure of the stream channel

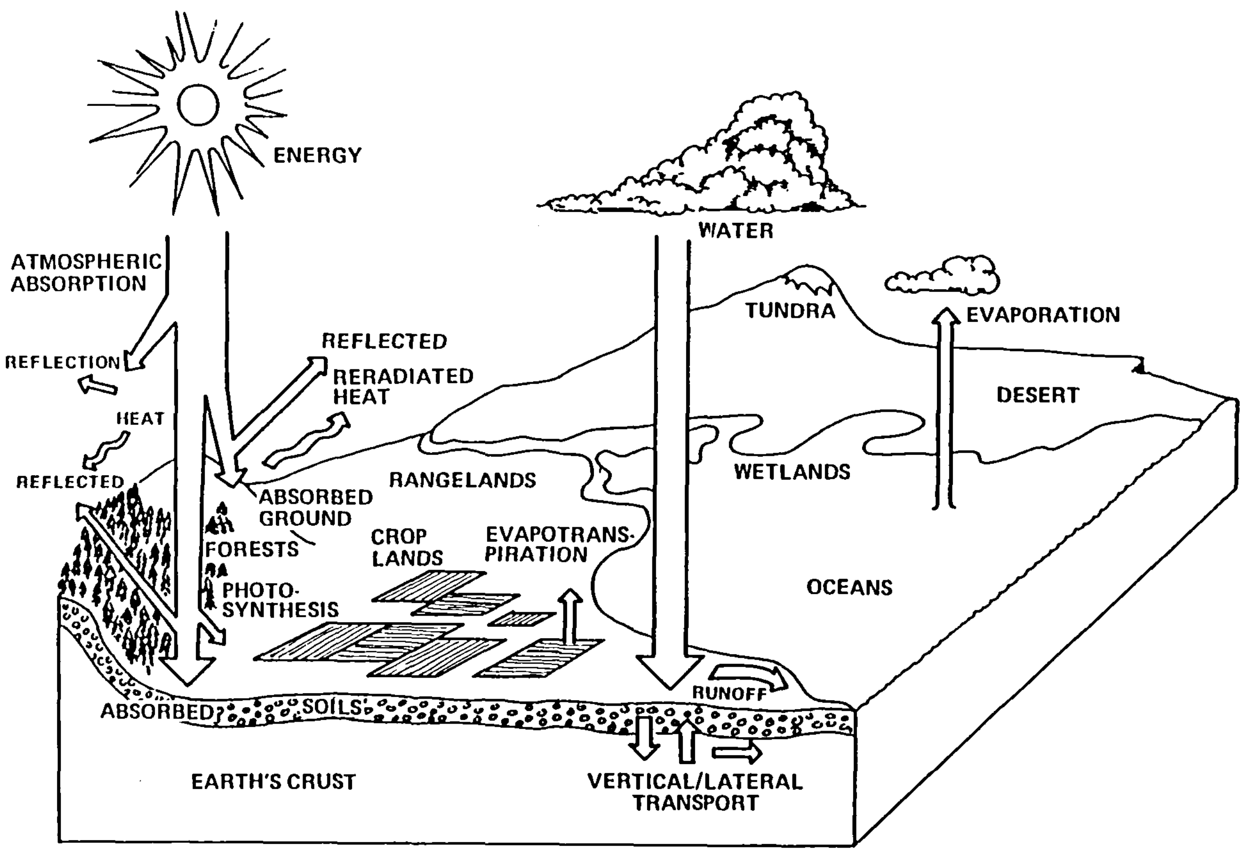

Figure 2 - Energy/Water Balance

and the diversity of the biological systems it supports are significantly influenced by the concentration and the character of these constituents. Their subsequent concentration in freshwater lakes and reservoirs is a cause of ecological change. These changes may be further complicated by acid rain.

Spatial variations of hydrologic behavior within a continent can produce significant differences in the quality of habitation on a regional basis. At the same time, these spatial variations provide the need for shifting water from areas of abundance to those areas having deficits.

Figure 3 can be used to illustrate some of the opportunities available for water redistribution for equalization of habitat quality. The average annual rainfall over the continental United States is in the vicinity of 4750 million acre-feet (maf). Seventy percent is evaporated or transpired. We supplement our surface water supplies by drawing 10 maf from groundwater reservoirs. We have 1380 maf of water moving through the river networks. We only withdraw 345 maf for human activity. Considering that 255 maf of this flow is returned to the stream networks, the U.S. discharges 1280 maf of the original 1380 maf into the oceans. Thus, there are significant opportunities for redistribution within the continent to increase productivities of large regions and to produce economic employment and other opportunities that characterize quality habitation.

2. Understanding the temporal and spatial feedback mechanisms that operate between climate and hydrology (Eagleson, 1982). The emphasis here is on regional-scale cause and effect relationships that are important in defining seasonal cycles, and the variability in seasonal and annual components of the hydrologic cycle.

During the winter months, the continents of Earth are sinks of atmospheric moisture picked up over the oceans, while in the summer, when thermal convection is the predominant precipitation mechanism, the depletion of soil moisture by evaporation and transpiration causes the continents to be sources of atmospheric moisture for subsequent precipitation on the land surface (Shulka and Mintz, 1982). The hydrologic cycle thus has different characteristic lateral scales in summer and in winter. Understanding these scales is vital in forecasting the location and size of anomalies in the cycle, and in defining the nature of the environmental impact of land surface change.

The storage and depletion of soil moisture, groundwater storage, and the growth of vegetation types all have characteristic time scales which determine the temporal persistence of hydrologic variation. These dynamic properties are central to modeling the perturbations, trends, and possible instabilities in land surface biological systems.

3. Monitoring the long-term change in the hydrologic cycle. Here the emphasis is on decadal changes at global scale. The task is to inventory, on a periodic basis, the liquid and solid fresh water stored on the land surface and in the soil, with the aim of detecting gradual change in the mean values (JPS, 1981).

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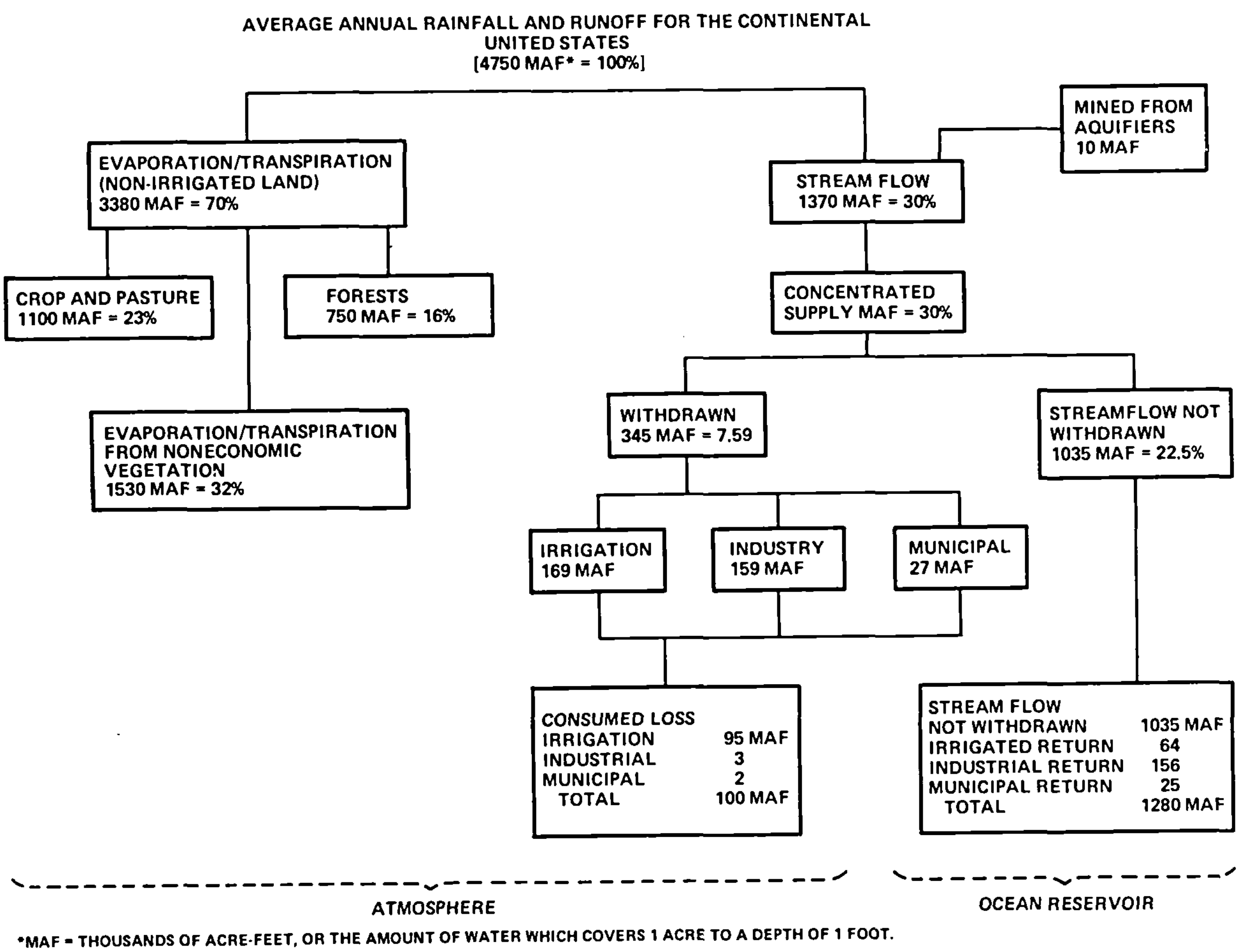


Figure 3 - Average Annual Rainfall and Runoff for the Continental United States

II.2.3 RESEARCH AREAS

The research areas presented in this section are grouped to support the time-spatial scales embodied in the three scientific issues presented in the previous section. The first group of research areas is required to develop a base for the local, relatively short-term modeling considerations of the first scientific issue. The second group addresses those problems associated with regional or continental-scale modeling and forecasting considerations. Finally, the third group of research areas seeks to examine those process interrelationships that define long-term, or climatic-scale, changes that characterize the third scientific issue.

1. Research required to define the distribution of the atmospheric forcings and physical parameters that enter into the prediction of soil moisture fluxes and the associated surface runoff.

Basically, the research associated with this issue seeks to significantly improve the accuracy of predictive models that address relative short-term, local-scale problems. Predicting monthly streamflow or groundwater elevations, the peak discharges during floods, and estimating the amount of water that will be available during periods of drought are examples of the types of problems that are associated with this first scientific issue. Obviously, hydrologists run models to make these predictions on a routine basis. However, serious gaps in our scientific knowledge frequently result in major errors in these predictions with sometimes catastrophic socio-economic consequences. Hydrologists must improve the accuracy of their models at this level before progressing to the much more complex, long-term simulations associated with interrelated continental scale problems.

A. Develop a series of test sites in different climatic regimes that will allow the proper definition of hydrologic parameters, and verification of models on a river basin scale.

There has been a massive commitment of resources worldwide toward the measurement of rainfall, streamflow, and grouna water elevations. Unfortunately, these data either have not been properly coordinated among collectors or have not been sufficiently complete to allow hydrologic interpretation. The problem has been further complicated by the absence of an efficient technique to manage and interface these data. The result is that there are no instrumented river systems that can presently be used to define our hydrologic models even at the current level of scientific understanding, much less to provide additional insights or information required for models at the level of sophistication required for improved habitability.

Fortunately, there are a number of river basins around the world that have the nucleus of the required data base that can be upgraded and structured to meet the needs of the first scientific issue. Further, computer-based information management systems can be implemented to provide the hydrologic scientist with a technique to manipulate, merge, and interpret massive quantities of data from an array of sources. Thus, a first step in the hydrologic research of the Global Habitability Program is the selection of a series of river basins in different climatic regions that already have a strong data collection

network that can be supplemented with additional in situ measurements and remotely sensed imagery to meet the needs of contemporary and future models. The availability of the data base from these test sites is pivotal to the success of the other research areas within this first scientific issue.

B. Develop an improved understanding of the dynamics of soil moisture, its hydrologic role, and our ability to model its behavior and influences.

The moisture stored in the soil determines the partitioning of precipitation into runoff and infiltration components. The soil moisture also affects the partitioning of solar insolation into latent and sensible heating components at the land-air boundary. Finally, the soil moisture reservoir has a direct and dramatic effect on the growth of vegetation and on global food production.

We need to conduct research that will allow us to develop a set of algorithms to use satellite remote sensing data to estimate soil moisture which account for the effects of soil roughness, type and texture, and vegetation, surface temperature, and other relevant features. There must be a conclusive set of methods to determine the soil moisture profile from surface soil moisture measurements for use in hydrological modeling and biological productivity modeling. In turn, this research will allow us to modify climatic, hydrologic, and agricultural productivity models to accept specific soil moisture and snow properties as input data.

Model the hydraulic properties of frozen soil and permafrost, and determine which sensor characteristics would be best suited to measure these features.

C. Develop an improved ability to measure and model the dynamics of snow cover.

It will be necessary to conduct fundamental studies employing radiative transfer modeling and field (laboratory) experiments to determine how the dielectric and optical properties of snow vary with depth, structure, and wetness of snowpack. We will also need to perform medium to large-scale experiments with airborne and satellite sensors to determine the amount and type of snow information that can be extracted by combinations of sensors at various frequencies. Representative examples of low-resolution radar, snow-cover mapping capabilities in mountain areas must be obtained.

D. Develop a capability centering on the combined remote sensing and in situ measurements that will provide a realistic definition of the temporal and spatial distribution of precipitation.

We must conduct precipitation estimation tests over land using active microwave, thermal, and visible systems. Hopefully, we can develop a universal precipitation estimation that will operate in a variety of study areas and for a variety of rainfall situations. In the final stages, this should lead to the development and implementation of a satellite precipitation monitoring system.

E. Develop a capability centering on remote sensing imagery that will allow realistic estimation of temporal and spatial rates of evapotranspiration.

Evapotranspiration is an important hydrologic cycle process because approximately 70 percent of the precipitation falling on the land surface is returned to the atmosphere via this route where it ultimately is the source of subsequent precipitation. It is vital to vegetation growth and also serves to protect the plant from overheating. As part of this research, we will test the utility of existing water balance models for estimating evapotranspiration over large regions using appropriate remote sensing inputs. In turn, we would move toward the utilization of advanced thermal IR data to determine surface temperature for input to models.

F. Develop or refine the capability to monitor, at streamflow gaging stations, the water-borne mass flux of sediment and of critical chemical elements such as carbon, nitrogen, sulfur and phosphorus.

Surface runoff and streamflow entrain and transport both solid mineral sediments and dissolved nutrients. Erosion represents a degradation of the landform and thus a change in its habitability, while subsequent deposition both impedes man's use of natural waterways and nourishes beaches. The water-borne flux of nutrients is an important link in the biogeochemical cycle of several elements.

G. Define the criteria for hydrologic similarity as they relate to habitability.

Generalization of hydrologic behavior is facilitated by recognition of the conditions defining dynamic similarity of seemingly disparate systems. Such recognition objectively amplifies data bases and isolates critical combinations of variables.

H. Verify the hypothesis that the natural vegetation canopy and the climate characteristics are sufficient to define the hydraulic properties of the soil.

Research on the average annual water balance has shown there to be a unique set of hydraulic soil properties in a given climate for which the natural canopy density of a given class of vegetation is a maximum under water-limiting conditions. It has been hypothesized that water-limited natural soil-vegetation systems may develop synergistically toward this climate-climax state. If true, this would greatly simplify the problem of setting parameters for the soil for global-scale modeling.

I. Determine the characteristic probability density functions for rainstorm area, soil properties, and vegetation properties.

Modeling the interaction of climate, soil, and vegetation at global scale necessitates representing the hydrology of large areas one-dimensionally. The important variability of atmospheric variables and system parameters across these areas will have to be treated stochastically, and the underlying

distributions must be determined by observation.

J. Incorporate spatial variability into one-dimensional hydrologic models using stochastic inputs and parameters.

The proper statistical-dynamic format for incorporating these variabilities must be determined.

2. Research required to improve our understanding of the temporal and spatial feedback mechanisms that operate between climate and hydrology.

A. Define the interactions between large-scale land transformation processes and regional/continental hydrologic behavior.

A number of key science issues must be examined within the context of a study of the interactions between large-scale land transformation processes and regional/continental hydrologic behavior. These issues are discussed in the following subsections.

(1) What are the interrelationships between land processes and shifts in the quantity and quality of available water?

It is generally recognized that land-use/cover changes, especially where large areas are involved, often cause significant changes in the quality or quantity of available water, as well as changing the timing of the runoff processes. Some of the key areas are: (1) sediment production; (2) lake eutrophication; (3) thermal pollution; (4) erosion and sedimentation; (5) lake and stream ecology; (6) flood and drought frequency; and (7) groundwater recharge.

(2) What is the impact of a change in albedo within a large area on regional/global hydrology regimes?

If one segment of an equilibrium system changes, then others must undergo some form of adjustment to return to an equilibrium condition. As discussed in the land use portion of this report, large segments of land are being transformed through either natural or man-driven processes. Deforestation, desertification, and urbanization/industrialization are among the most dramatic. Significant changes in albedo are characteristic of such changes.

It is well established, as in the case of the areas around St. Louis, Missouri, that large urban "heat islands" can produce easily measured increases in precipitation downwind. We need to understand what happens in the surrounding regions and on a global basis when the size of the heat island is increased manifold as happens in deserts. If we can develop sufficient understanding to model the impact, we can anticipate it and make preparations because desertification is a transitional rather than an instantaneous process. Knowledge of the reflectance, transmittance, and absorptance of vegetative, water, and other surfaces is necessary to understand the energy balance within an ecosystem. Reflectance, transmittance, and absorptance measurements of vegetation canopy components (leaves, stem, reproductive elements, stalks, limbs, etc.), soil rock and other barren surfaces (as a function of soil type, moisture, and surface roughness), and water bodies (as

a function of sedimentation, vegetation and depth), should be made at visible, reflective, and thermal infrared wavelengths.

To obtain estimates of the radiation characteristics of the sites, these reflectance, transmittance, and absorptance data must be used in conjunction with data on the spatial and temporal distributions of site surface types and their physiognomic characteristics (leaf area index distribution, phenological stage, etc.) and surface reflectance models.

While it is usually assumed that the land-atmosphere system is in a state of dynamic equilibrium, this is not necessarily true. The passing of the daily and seasonal cycles of metabolic activity and warming and cooling is reassuring, but the polar ice caps and abundant glacial debris remind us that other climatic states are possible, even probable. The "year with no summer" in 1883 after the eruption of Krakatoa, the discovery of buried streambeds in the Egyptian deserts, and the recollection of childhood memories of woods where shopping centers now stand, all testify to change. It is more than simple change that we fear, it is irreversible change. The rapid expansion of the Sahara Desert in the 1970's can be understood in terms of a positive feedback between overgrazed lands and the ever-drier atmosphere (Charney, 1975).

Models must be developed which relate observed properties of the land cover and climate to changes in the land cover. Testable hypotheses exist for desertification which relate changes in albedo and evapotranspiration to an altered precipitation regime. Similar process studies should be done for the impact of large-scale deforestation on precipitation and soil loss. The ability of tropical forests to reestablish themselves after attempted conversion should be investigated.

More detailed measurements of specific sites are required to establish the hemispherical albedo, the heat capacity, the type and magnitude of biogeochemical reservoirs, and the emission rates of biogeochemical species. A series of research tasks to address these parameters is addressed in the following paragraphs and elsewhere in this report. For the purposes of the land-air interchange studies, it is necessary to utilize global land cover maps to obtain a full global representation of the Earth's properties. The requirements for the land cover mapping are not identical with those of other investigations. For many aspects of the problems, only low resolution mapping is required, and the final product should be aggregated to the climate grid scale (250 Km). High-resolution measurement will be required for subgrid scale characteristics such as the types of biogeochemical reservoirs.

B. What is the role of spatially varied evapotranspiration on regional/continental scale hydrologic regimes?

Evapotranspiration has a profound influence on the amount of moisture flow characterizing the hydrologic regime of a region. Indeed, there is general agreement that plant type and its biomass within a region has evolved to its state as an equilibrium response to transpiration conditions. Thus, in this context, transpiration can be viewed as a selective process by which a given species diversity and density has become established. A plant's height, leaf

area and shape have evolved to optimize its ability to transpire under a given set of soil moisture and atmospheric conditions (Grier and Running, 1977). These conditions may be further adjusted to reflect differences in soil type, elevation, or the aspect of location. This equilibrium concept is a hypothesis, and there have not been any experiments of sufficient scale and length to quantify the relationships. Quantifications of the concept could be invaluable in determining the consequences of water shortages, or in selecting plants for use under conditions of water imports to supplement local supplies.

Because it is well-recognized that vegetation transpires significant quantities of moisture back into the atmosphere, many efforts have been made to increase water yields through the management of vegetative cover. With few exceptions, these efforts have been counter-productive because of our lack of understanding. The volume of runoff increases, but it comes off very rapidly and cannot be properly used because the length of the cycle is much shorter than before. Further, there are tremendous problems with soil erosion. Finally, after a few years, plant regrowth has reached the point that the volume of runoff is no greater than before the process started. There are gains to be made in plant manipulation for managing water yields, but we do not have the scientific base needed to do it intelligently or even safely.

We must develop a sufficient understanding of the evaporation process to be able to model it in both an operational and predictive mode. Regional scale transpiration models are very weak and, as a result, many incorrect policy decisions are made. Recently-developed measurement capabilities through space platform remote sensing have the potential to provide key input data for physiologically-sound transpiration models. We now have to develop an understanding of regional scale transpiration processes in order to design the appropriate models.

C. What are the consequences of rapid increases in water supply to a region, such as occurs in major interbasin transfers, on the local and larger scale hydrologic cycles?

Large-scale engineering schemes for diverting water from one area to another, usually for irrigation, are as popular today as they were 2,000 years ago. Unfortunately, such projects sometimes generate even more expensive schemes to correct the problems created by the first project. For example, irrigation without adequate drainage is disastrous in the long-run and destroys the land for crops. As it flows downward through the ground strata, water dissolves salts of sodium, calcium, magnesium, and other substances. If these excessive dissolved salts are not drained from a water basin as fast as they enter, evaporation will cause salt to build up in the soil and groundwater. This problem exists in the southwest United States, California, and the Punjab region of Pakistan, and in many other heavily irrigated areas with inadequate drainage.

In addition, the diversion of freshwater rivers into marine ecosystems has the potential for changing the micro or macroclimates of a region. For example, the USSR has a grand scheme for reversing the flow of the Pecnora and Vychegda rivers to irrigate the warm valleys in the south, and to prevent further decline of the level of the Caspian Sea. If the USSR were to succeed in

reversing these rivers, and Canada and the United States were to turn around the Canadian rivers now flowing into the Arctic Ocean (e.g., in the North American Water and Power Alliance water diversion scheme), there might be large and unpredictable changes in ocean currents that transport warm and cold water. These, in turn, could cause serious shifts in world and regional climates, and change ecological patterns of plant and animal life in the oceans (Miller, 1975).

As the remaining available uncommitted supplies of water and land resources diminish, and demands for them increase, the objectives of water resources planning broaden, the physical facilities required become more complex, and the limitations under which they must be implemented become more stringent. There exists an urgent need to develop sophisticated mathematical techniques applied on digital computers of increasing speed and accuracy which can enhance the capability of the planners to make intelligent and comprehensive evaluations of alternatives. This need has been met, in part, through the use of systems analysis techniques which have attempted to model the complex temporal and spatial variations of water quantity and quality parameters in rivers, lakes, and estuaries. Besides modeling the water parameters in a water body, collection and treatment facilities, regional water supply systems, and local sewer systems, a comprehensive large area regional water resource management plan (e.g., Texas Water Plan) can be assessed.

D. What is the impact of natural and man-driven disturbances on coastal and inland wetlands?

The importance of wetlands can be related to their dominant role in element cycling. These ecosystems are also the primary terrestrial source of many reduced gases in the Earth's atmosphere. Modifications of wetlands, whether by natural succession, episodic events, or human activities, reduce their ability to regulate terrestrial inputs from the associated watershed.

Wetlands modification within coastal watersheds, particularly those of less-developed countries, are generating demands to quantify the impacts associated with reductions in wetlands biomass. However, less-developed countries are unable to formulate monitoring and conservation programs; therefore, information concerning the specific roles and values of wetlands may be acquired after irreversible damage is done to some wetlands ecosystems (e.g., mangrove forests).

Localized effects of wetland biomass reduction are manifested in reduced water quality, reduce coastal productive capacity, and reduced shortline stability.

E. Define the mechanisms and scales of both the temporal and spatial feedback of moisture and sensible heat from the land surface to the hydrologic forcing.

To deal effectively with the environmental impact of land surface changes such as deforestation, swamp drainage, and urbanization requires that we understand and be able to formulate the effects that changes in the land surface fluxes of heat and moisture have on the atmospheric temperature and humidity which drive these processes. This understanding will lead to forecasts of the

extent and severity of environmental change, and may uncover critical system instabilities that make sudden climatic shifts possible.

3. Research required to monitor the long-term changes in the hydrologic cycle.

A. Inventory the fresh surface water (including ice) periodically on a global basis.

Change in the global hydrologic cycle should be detectable through monitoring the volume of stored water.

B. Define sensitive measures of hydrologic change. Where will long-term change be most noticeable? Will it be in the area of perpetual snow cover, in the amplitude of seasonal oscillation of the snowline, in the volume or limit of glaciers, in the tree-line, etc.?

C. Analyze the time-stream of inventories statistically, seeking early indications of regional trends and verification of models.

Here we have the impossible problem of detecting long-period change from a short-period record. Models of the system dynamics will help with the inference, but there is no substitute for continued data collection. The repeated inventories will be valuable, eventually, in verifying global models of hydrologic change.

II.2.4 MEASUREMENT REQUIREMENTS

For determination of the world water balance, the needed measurements include global averages of atmospheric water vapor, ocean area and volume of water, surface area covered by rivers and lakes (and companion data on conversion to volume), global average soil moisture storage, groundwater volume, and volume of water in ice caps and glaciers. For specific studies, we want to measure the soil moisture in the upper 5-10 centimeters of soil, snow-cover extent and depth, snow-cover water equivalent and wetness, precipitation amounts, and evapotranspiration rates.

II.3 BIOGEOCHEMICAL CYCLES

II.3.1 INTRODUCTION

Habitability of the earth's land surfaces by plants and organisms depends on the cycling of material in the biosphere. Plants and animals are viable only if the elements necessary for life are available. Among the approximately 40 elements required are carbon, nitrogen, phosphorus, sulfur, oxygen, calcium, magnesium, potassium, sodium, silicon, iron, and aluminum. Exchanges of these elements between the relatively large abiotic reservoirs, such as the atmosphere and sediments, and the biotic reservoirs comprised of plants and organisms, constitute the biologically associated pathways crucial to land habitability. This interaction between biotic and abiotic components in the element cycles distinguishes the earth from other planets and motivates the term biogeochemical cycling.

The general objective of this part of NASA's Land-Related Global Habitability Research Program is to further our understanding of the role of terrestrial ecosystems in the global biogeochemical element cycles and, in turn, to study the effects of changes in these cycles on the structure and function of terrestrial ecosystems.

The global element cycles are inescapably coupled with the earth's energy balance and hydrologic cycle. The biogeochemical element cycles support biological productivity on land but, at the same time, are maintained in large part by functions of plants and organisms. The assimilation of carbon from the atmosphere by photosynthesis, incorporation by consumer organisms, and release back to the atmosphere by decomposition is the fundamental pathway for material cycling through terrestrial ecosystems. Assimilation by photosynthesis is driven by solar energy, and water is a primary constituent of this biological process.

A major difficulty in studying the dynamics of the global biogeochemical cycles is the spatial heterogeneity inherent in the terrestrial components of these systems. Pathways of element cycling differ in relative importance in different ecosystems and, even within regions of relatively uniform ecology, there is substantial spatial variability in the character of element cycles. Under natural conditions, this heterogeneity in the terrestrial element cycles is the consequence of variability in factors such as microclimate, substrate, vegetation, and frequency of disturbance by fire or weather anomalies.

Land-use change and other human disturbances have substantially complicated the study of the global element cycles. Under natural conditions, the distribution of terrestrial ecosystems is determined in large part by climate, parent material for soil formation, and other physical factors. The element cycles in terrestrial ecosystems or even at the global scale can generally be considered to conform to a steady state on time periods sufficiently long to average over the occurrence of sporadic natural disturbances such as fire and weather anomalies. However, during the past several centuries, human disturbances, particularly land-use changes such as forest clearing, have drastically altered the landscape and the structure and function of terrestrial ecosystems

(e.g., Woodwell 1978, Bormann and Likens 1979, Houghton et al. 1983). As a result, the global element cycles have changed and, in so doing, have induced changes in terrestrial biological processes.

An immediate consequence of the variability in the element cycles on land is the necessity for obtaining measurements from a large number of representative ecosystems. A good deal of information is available in the scientific literature, but more systematic approaches are needed, and in many instances, new techniques are required to measure key properties. Development of instrumentation both for onsite use and for remote sensing is an important aspect of this project.

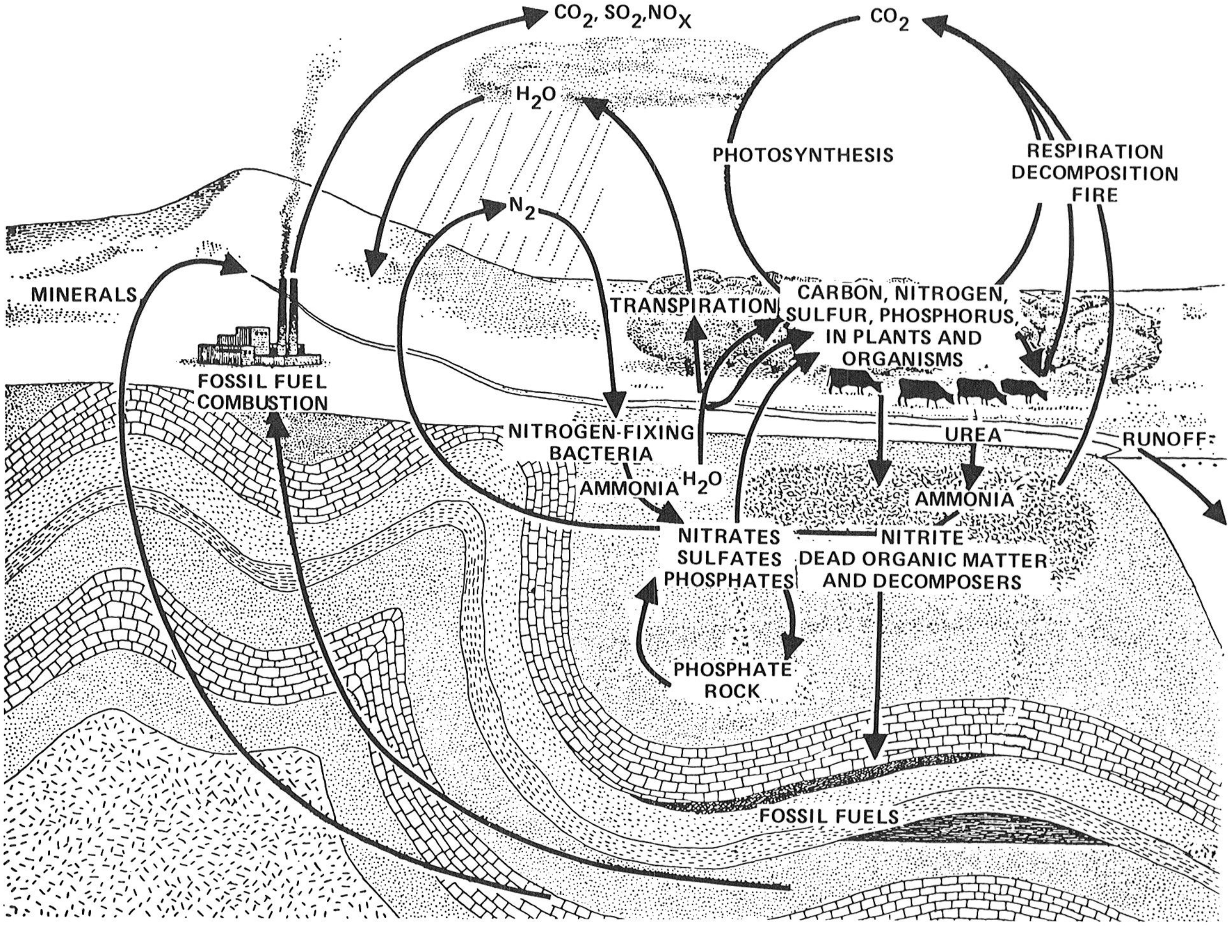
Land-cover assessments are fundamental to biogeochemical cycling studies. Remote sensing data is critical to a satisfactory accounting of spatial variability in studies of the element cycles on land. Many intensive onsite studies are necessary for calibration; however, remote sensing is the only practical method for quantifying variance over large landscapes and continents. In addition to land-cover, the climate, microclimate, biological productivity, and other factors will be remotely sensed to quantify the distributions of properties which affect the element cycles.

Detailed understanding of element cycling in particular kinds of ecosystems, derived from intensive measurement programs at key sites, will be used to formulate mathematical models for each major ecosystem complex. Simulations with these models will be combined with maps and models indicating changes in areal extent of major ecosystem complexes to analyze element cycling at the global scale. As a basis for projecting changes in the global element cycles, these spatially detailed global models will be applied to simulating historical changes in the cycles over the past several centuries, which in turn will form the basis for predicting the nature of future changes which may occur as a result of further human disturbance. Finally, sensitivity studies will indicate variables which are important to monitor for future changes in the cycles.

<u>Background</u>

Four elements, carbon, nitrogen, phosphorus, and sulfur, in addition to water, are almost uniformly necessary for sustaining life in terrestrial ecosystems. The carbon and nitrogen cycles include gaseous exchanges between terrestrial ecosystems, and the relatively well-mixed atmosphere interacts with both terrestrial and marine components. In contrast, terrestrial cycles of elements such as phosphorus, calcium, and numerous trace elements involve interactions among plants, organisms, the soil-water solution, and sediments and are much more localized to particular ecosystems. Figure 4 is a general schematic of the cycles of the four major elements: carbon, nitrogen, phosphorus, and sulfur.

Carbon cycling in terrestrial ecosystems and exchanges of carbon between the atmosphere and these systems are a major manifestation of biological productivity on land. Carbon is assimilated from the atmospheric CO(2) pool by photosynthesis and stored in plants. Subsequently, it may be incorporated by consumer organisms or, as a result of plant mortality, pass directly to the



Schematic diagram of the major biogeochemical element cycles. The carbon cycle is the focus of material transfer through the biotic components of the cycles. Carbon is assimilated from the atmosphere by photosynthesis and released from pools of dead organic matter in the litter and soil by decomposition and fire. Nitrogen also has an important atmospheric component; however, the nitrogen cycle is quite complicated because of the role of microorganisms in fixing nitrogen from the atmosphere and transforming organic nitrogen to forms usable by plants. The cycles of other elements such as phosphorus do not involve significant atmospheric exchanges and operate primarily in the below ground component of terrestrial ecosystems. (Drawing is after Hutchinson)

Figure 4 - Cycles of the Four Major Elements

pools of dead organic matter in litter and soil. Carbon is returned to the atmosphere by decomposition of dead organic matter. The processes of decomposition rely on organisms in litter and soil and are sufficiently complicated so that the age of carbon in these reservoirs compared to the atmosphere ranges from several years to several thousand years.

There is a large pool of nitrogen in the atmosphere (79% by concentration) in the form of molecular nitrogen N(2); however, this gaseous form of nitrogen can be used only after conversion to a form usable by plants and organisms. The world's terrestrial ecosystems rely on microorganisms to fix molecular nitrogen (N(2)) from the atmosphere as inorganic compounds (ammonia NH(3), nitrite NO(2), and nitrate NO(3)) in the soil-water pool that are usable by plants. The fixation of free nitrogen from the atmosphere is accomplished by nitrogen-fixing bacteria, some of which are symbiotic in that they live in the root-nodules of the plants they supply with nitrogen. Nitrogen fixation is a key example of the maintenance of biogeochemical cycles by the organisms which they support. The fraction of nitrogen fixation due to free-living microorganisms remains unclear.

Once nitrogen is incorporated in organic compounds, it must be converted again to an appropriate inorganic form before it is reusable by plants. Nitrogen in organic form (urea, protein, nucleic acids, or as organized protoplasm in dead organisms) is converted to ammonia, a form useful to plants, by microorganisms which release energy in this process, referred to as ammonification. Ammonium nitrogen can be taken up by plant roots in this form or oxidized to nitrite or nitrate by additional microbial processes and then recovered by some plants.

Although some plants are specific in terms of the inorganic form of nitrogen they use (i.e., nitrate nitrogen or ammonium nitrogen), most plants can use either type. Table 2, attributed to Ellenberg 1971, indicates the distinction in the form of inorganic nitrogen used by plants in a number of types of terrestrial ecosystems.

The relative abundance of phosphorus in plants and organisms, compared to other elements, tends to be substantially greater than the proportion in primary sources, implying that phosphorus is frequently limiting to biological productivity. Abundant pools of phosphorus exist, but they consist almost entirely of insoluble and therefore biologically inaccessible forms. Plants require inorganic phosphate principally as orthophosphate ions (PO(4)). Again, decomposer organisms mineralize organic phosphate to complete the cycle. There is no stable gaseous form of phosphorus, and inputs of phosphorus from the atmosphere to terrestrial ecosystems occur as dry deposition or with precipitation. A substantial amount of phosphate is lost to the sea by runoff and deposited in sediments. The mechanisms for returning this phosphate to land include transport by birds and other animals that inhabit both land and water environments, and may be inadequate to compensate for losses.

Sulfate (SO(4)), like nitrate and phosphate, is the principle form used by plants. Again, the microorganisms are responsible for breaking down sulfur-bearing organic compounds into H(2)S, elemental sulfur, or finally SO(4) which are usable by plants. Sulfur is not required by plants and animals in amounts as large as for nitrogen and phosphorus and is generally not limiting to

NH_4^+–type	NH_4^+ – NO_3^-–type	NO_3^-–type
Taiga, dwarf-shrub tundra	Many temperate deciduous forest on loamy soil	Moist tropical lowland forest
Subalpine coniferous forest	Alluvial forest	Temperate deciduous forest on calcareous soil
Coniferous peat forest	Alder fen *(A. glutinosa)*	Fertilized meadows where soil is not wet, most gardens
Oak-birch forest	Many grassland types	
Calluna heath	Dry grassland on calcareous Soil	Ruderal formations
Many swamps	Tropical savanna	
Raised *Sphagnum* bog	Some tropical forests	

Table 2 - Ecosystem Types classified by the Main Forms of Mineral Nitrogen (from Ellenberg, 1971)

biological productivity in terrestrial ecosystems. Changes in the sulfur cycle can be reponsible for major changes in ecosystems. Exposure of metallic sulfides to air can result in microbial production of sulfuric acid in terrestrial watersheds.

Elements such as calcium and magnesium are important in particular types of ecosystems. Like phosphorus, the cycles of these elements are essentially localized and do not include a significant atmospheric component. Maintenance of biological productivity in the particular ecosystems in which they are important depends on the cycles of these elements as well as those of the major elements: carbon, nitrogen, phosphorus, and sulfur. The cycles of trace compounds in terrestrial ecosystems are comprised in large part of the pathways of the major elements; however, specialization by particular organisms in transforming certain compounds may make these cycles more susceptible to change than those of the major elements.

Through biogenic emissions from both soil microorganisms and the above ground biomass, the biota have a major influence on the constituents of the atmosphere, particularly the trace compounds (e.g., Bremmer 1977, Crutzen et al. 1979). The species and rate of release of these volatiles are closely tied to environmental conditions and stress. For example dinitrogen oxide (N(2)O) is present at relatively low (~10 ppb) background levels, but during short periods, "bursts" of N(2) can increase several orders of magnitude. Anaerobic microorganisms under the influence of specific soil moisture, temperature, and physical-chemical properties are responsible for this enrichment and, typical of many emission characteristics, vary widely in space and time. Various sulfur nitrogen compounds in the atmosphere originate from vegetation, and their releases can be changed drastically by disturbance such as land clearing, biomass burning, or fertilization.

Under natural conditions, the distribution of terrestrial ecosystems is dictated in large part by climate and the character of parent material for soil formation. Further, in essentially natural ecosystems, inputs and losses of material approximately balance, so that on sufficiently long time periods, the terrestrial components of the element cycles may be assumed to be in steady state. At shorter time scales, the balance certainly shifts with changes in nutrient availability, climate, and sporadic disturbances (e.g., Olson, 1963; Bormann and Likens, 1979). Over the past several centuries, human disturbances, particularly land-use change, have drastically modified the distribution of terrestrial ecosystems and perturbed the element cycles in these systems from any steady state which may have been sustained prior to human intervention. In addition to direct impact on the world's land systems, man's activities have also affected abiotic reservoirs in the atmosphere which interact through the biogeochemical cycles with pools in terrestrial ecosystems.

Perturbations to the global carbon cycle are the best documented of man's impacts on the global element cycles. Measurements of CO(2) concentration at Mauna Loa Observatory, Hawaii since 1958 (Keeling et al. 1976) as graphed in Figure 5, as well as shorter records at additional stations, indicate a systematic increase that is attributed primarily to fossil fuel combustion. At Mauna Loa, annual average CO(2) concentration increased from approximately

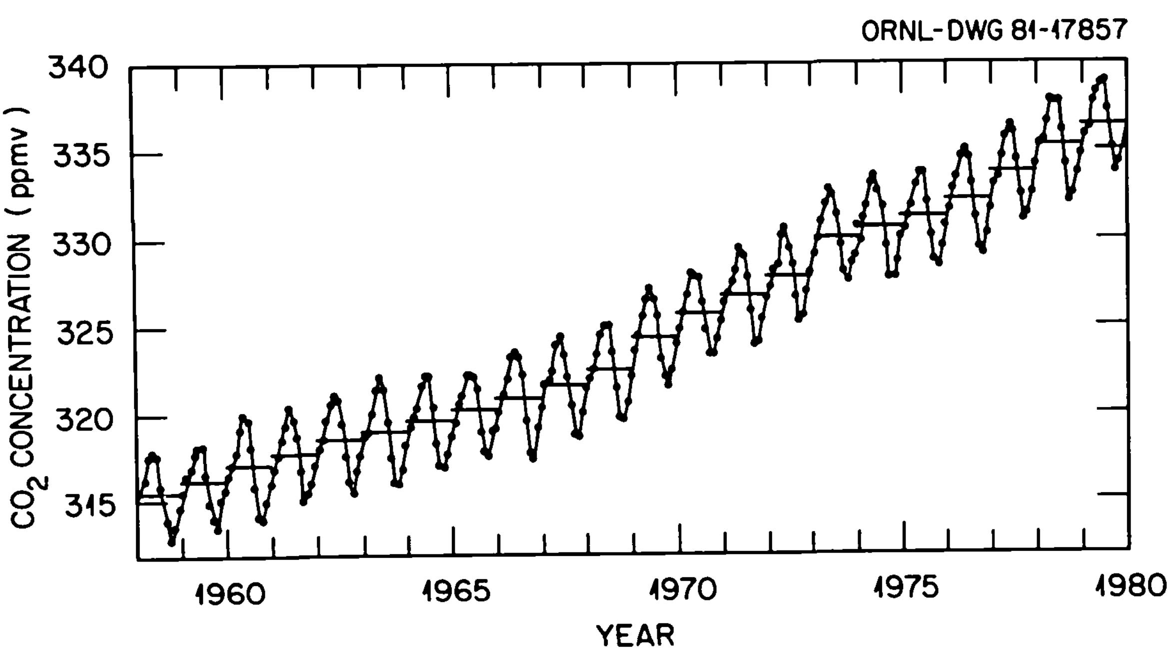


Figure 5 - Measurements of Atmospheric CO^2 Concentration (Recorded at Mauna Loa Observatory, Hawaii)

316 ppm in 1959 to over 338 ppm in 1980. This increase corresponds to about 54 percent of the estimated release of CO(2) by fossil fuel use during this period (e.g., Rotty 1981, Bacastow and Keeling 1981). The observed change in the carbon content of the atmosphere is less than the cumulative input from fossil fuel combustion and any additional sources as a result of carbon exchanges between the atmosphere and other reservoirs, particularly the oceans and terrestrial ecosystems (e.g., Baes et at. 1977; Bolin et al. 1979).

The balance between assimilation by photosynthesis and releases of carbon from both living and dead material dictates the magnitude of the net exchange of carbon between the atmosphere and the world's terrestrial ecosystems. During the period of substantial CO(2) releases from fossil fuels, disturbance to terrestrial ecosystems by human activities, particularly forest clearing and other landuse changes, have been the dominant influence in determining the net transfer of carbon between terrestrial ecosystems and the atmosphere (e.g., Bolin 1977; Woodwell et at. 1978).

With land-use change such as forest clearing, carbon is immediately released to the atmosphere by burning, or with a delay, by decomposition. In many instances, ground vegetation or annually harvested crops rather than trees are established after clearing, and by management this conversion may continue indefinitely with a lower carbon storage than in the original ecosystems. Following clearing or a similar disturbance, net productivity generally exceeds losses, and disturbed ecosystems may act as sinks for carbon from the atmosphere for some time.

Over the past several centuries, different regions of the world's land surface have been sources or sinks for carbon from the atmosphere at different points in time depending on the patterns of human disturbance. To reconcile estimates of the releases of CO(2) to the atmosphere with the observed changes in CO(2) concentration, the details of these historical changes in terrestrial carbon storage must be reconstructed with reasonable accuracy. This reconstruction requires an accounting of both the changes in areal extent of major ecosystem types, and the impact of disturbance on carbon storage in particular ecosystem types.

As CO(2) concentration in the atmosphere increases, plant productivity may be stimulated in some ecosystems. However, competition for light, nutrients, and water determine standing crop in most instances so that the effects of CO(2) fertilization remain uncertain. Additional carbon storage in terrestrial ecosystems over the period of reliable atmospheric CO(2) measurements as a result of CO(2) stimulation of photosynthesis is an important factor in the interpretation of CO(2) time series; however, at present, there is no satisfactory way of assessing the magnitude of this effect at the global scale.

When humans burn fossil fuels, they not only release large amounts of carbon into the atmosphere, but inputs of nitrogen and sulfur also occur, some of which may enter terrestrial ecosystems in bulk precipitation. This rise in available nitrogen may stimulate both carbon fixation and storage in, for instance, forest ecosystems. Conversely, wood harvests can reduce not only the carbon stock of forest ecosystems, but the nitrogen stock as well. First,

nitrogen leaves the forest in harvested material. Second, erosion accelerated by the harvest carries off nitrogen-bearing soil. Third, forest cutting can dramatically raise losses of inorganic nitrogen, principally nitrate removed in solution by streams that drain cutover areas. Wood harvests may also stimulate denitrification, creating a fourth possible pathway for nitrogen loss.

Changes in soil nitrogen content may have a more pronounced effect in the longer term since vegetation recovery may be limited by nitrogen availability. In annually harvested agriculture, a consistent decrease in soil nitrogen content with years of cultivation has been noted by several investigators. Figure 6 illustrates this decline in soil nitrogen for croplands in the central United States (Jenny, 1941). To overcome the deficiencies in soil nitrogen resulting from agriculture and other human activities, man has made widespread use of nitrogen fertilizers. Summarizing data from the United Nations and several literature sources, Soderlund and Svensson (1976) estimate the industrial fixation of nitrogen to have been approximately 36 X 10(12) g N in 1970, and 53 X 10(12) g N in 1975. This intervention in the nitrogen cycle by man may eventually prove to be a substantial disturbance.

Depending on soil moisture, soil temperature, and physical and chemical properties of soils, fertilization and denitrification processes can lead to "bursts" of N(2)O, or change the proportion of emissions leaving the soil surface between NO(3), NH(3), and N(2)O. This proportion is critical because N(2) is very stable at low altitude and diffuses to the stratosphere where the higher activation energies of solar ultraviolet radiation can cause transformation to NO(x) compounds. These compounds then react with ozone to remove O(3). The spatial and temporal variability in N(2)O emissions are very high with four orders of magnitude variation in flux levels, making analysis of this interaction with the atmosphere difficult.

Human activity has altered the availability of phosphorus in both direct and indirect ways. The application of phosphorus fertilizer is a direct perturbation, but more subtle alterations of the phosphorus cycle may influence the dynamics of the other cycles as well. Fire, either natural or as a management technique, may increase the available stocks of phosphorus, since oxidation of plant litter transforms organically-bound phosphorus into usable forms. Increased levels of available phosphorus can, in turn, raise the rate of nitrogen mineralization in soil.

On a global scale, the sulfur cycle is assuming increasing importance, as the full impact of acid rain and atmospheric sulfur pollution become clearer. Indirect calculations suggest that emissions of gaseous sulfur to the atmosphere from fossil fuels are already on the same order of magnitude as releases from natural systems. High rates of sulfate reduction and periodic tidal exposure to the atmosphere combine to make coastal wetlands prime sources of atmospheric sulfur. Clearly, the biogenic sulfur fluxes are large, yet few direct measurements are available, and the requisite techniques are still uncertain.

Mathematical models provide a means of summarizing the global element cycles in a framework which permits testing of hypotheses and analysis of scientific

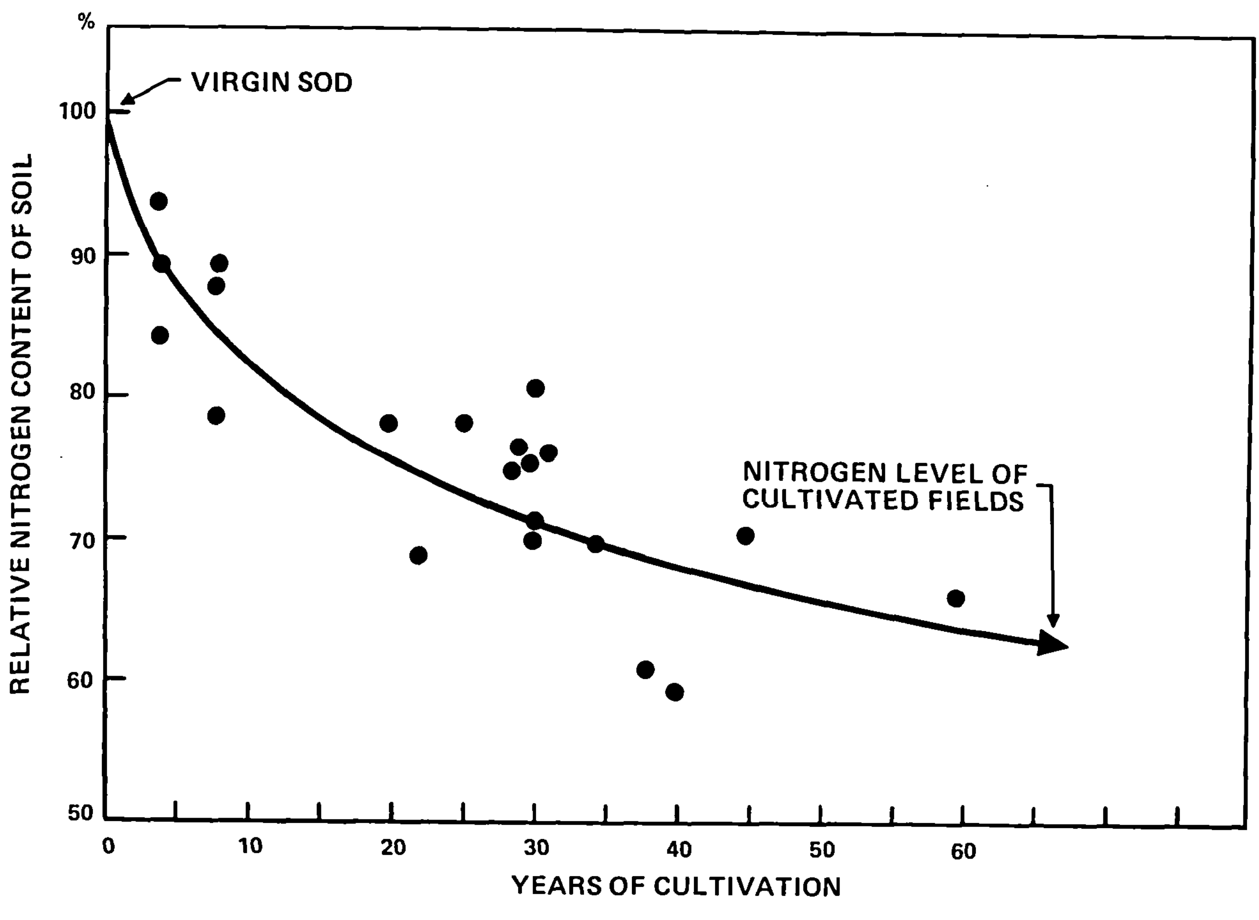


Figure 6 - Soil Nitrogen Content vs. Years of Cultivation

issues. Several investigators have proposed global scale compartment diagrams for the major element cycles (e.g., carbon: Bolin et al. 1979; nitrogen: Soderlund and Svensson, 1976; phosphorus: Pierrou, 1976; sulfur: Ivanov, 1981); however, only in the case of carbon have models been widely presented (e.g., Bolin, 1981). Carbon cycle models continue to be unsatisfactory in resolving observed changes in that cycle with estimates of historical perturbations by fossil fuel combustion, land-use change, and other disturbances, and the representation of terrestrial carbon storage in these models is perhaps their weakest aspect.

In the Land-Related Global Habitability Research Program, biogeochemical element cycling research will focus on development of spatially-detailed data sets and models. The goal is to improve our understanding of the terrestrial components of the cycles and their interactions by addressing spatial variability and the effects of human activities on the distribution of terrestrial ecosystems with more sophistication than has previously been possible. Data on the element cycles in each major type of terrestrial ecosystem will be assembled from site studies and used to calibrate compartment models. Remote sensing data on the areal extents of major ecosystem complexes and on the structure and function of terrestrial ecosystems in the cycling of major elements will be used to provide a spatial basis in integrating these models to a global framework.

II.3.2 SCIENCE ISSUES AND THEIR IMPORTANCE

Science issues which must be addressed in the study of the global biogeochemical cycles include:

1. Description of the dynamics of the major element cycles (including C, N, S, P) with sufficient global and biogeographical detail to estimate the state of, and changes in, pools and fluxes which result from human or natural disturbance, particularly land-use change and variations in climate.

2. Evaluation of the interactions and couplings among the major element cycles, their nominal ratios, and shifts due to disturbance.

3. Determination of the role of the biota and associated linkages through climate in controlling and stabilizing the element cycles.

4. Description of the dynamics of trace elements associated with the major elements (e.g., those associated with the trace gases CH_4, H_2O, H_2S, NH_3).

5. Documentation of the history of changes in the major element cycles over the last decade to several centuries as a basis for verifying models and making future projections.

6. Determination of the variables and processes which are important to monitor as indicators of changes in global element cycles.

II.3.3 RESEARCH AREAS

To address the scientific issues outlined above, research in a number of major areas is required. These areas include tasks to:

1. Collect and synthesize detailed data on the processes and factors which control element cycling in each of the world's major terrestrial ecosystem types.

2. Develop relationships between properties of the terrestrial element cycles and environmental factors such as climate and substrate.

3. Develop relationships between key variables and parameters monitored at field sites and remotely sensed data.

4. Quantify variability in the terrestrial element cycles due to spatial heterogeneity.

5. Develop models for the element cycles in each of the world's major terrestrial ecosystem types which incorporate the dependence of the cycles on the environment and satisfactorily treat spatial variability.

6. Incorporate land-cover and other information reflecting the areal extent of applicability of element cycle models to provide a capability to simulate dynamics of the cycles at the world scale.

7. Combine world element cycle models and histories of land-use change derived from remote sensing and other sources to simulate changes in pools and fluxes over the past decade to several centuries.

8. Apply models, data bases, and remote sensing capabilities to project future changes in the global biogeochemical cycles.

The following discussion elaborates these research areas more fully and provides some indication of the ordering of tasks and priorities. Figure 7 is a schematic indicating the general relationship of these research areas in a global biogeochemical cycling research effort.

Site Studies and Calibration of Remotely Sensed Data

The details of the element cycles in terrestrial ecosystems can only be discerned through intensive measurement programs implemented at representative sites. Study areas with ongoing data collection have been established by many research groups, and additional studies at sites that are not continually monitored or are reported in the literature. Two general shortcomings limit the usefulness of these data in studying the global element cycles: (1) many types of ecosystems and regions are inadequately represented; (2) quantities are not consistently measured at different sites, and many important variables are rarely measured. The Land-Related Global Habitability Research Program will work to improve the world scale monitoring of terrestrial element cycles throughout the duration of the Program. Initially, extent data will be assembled and models derived to aid in establishing priorities for refinement,

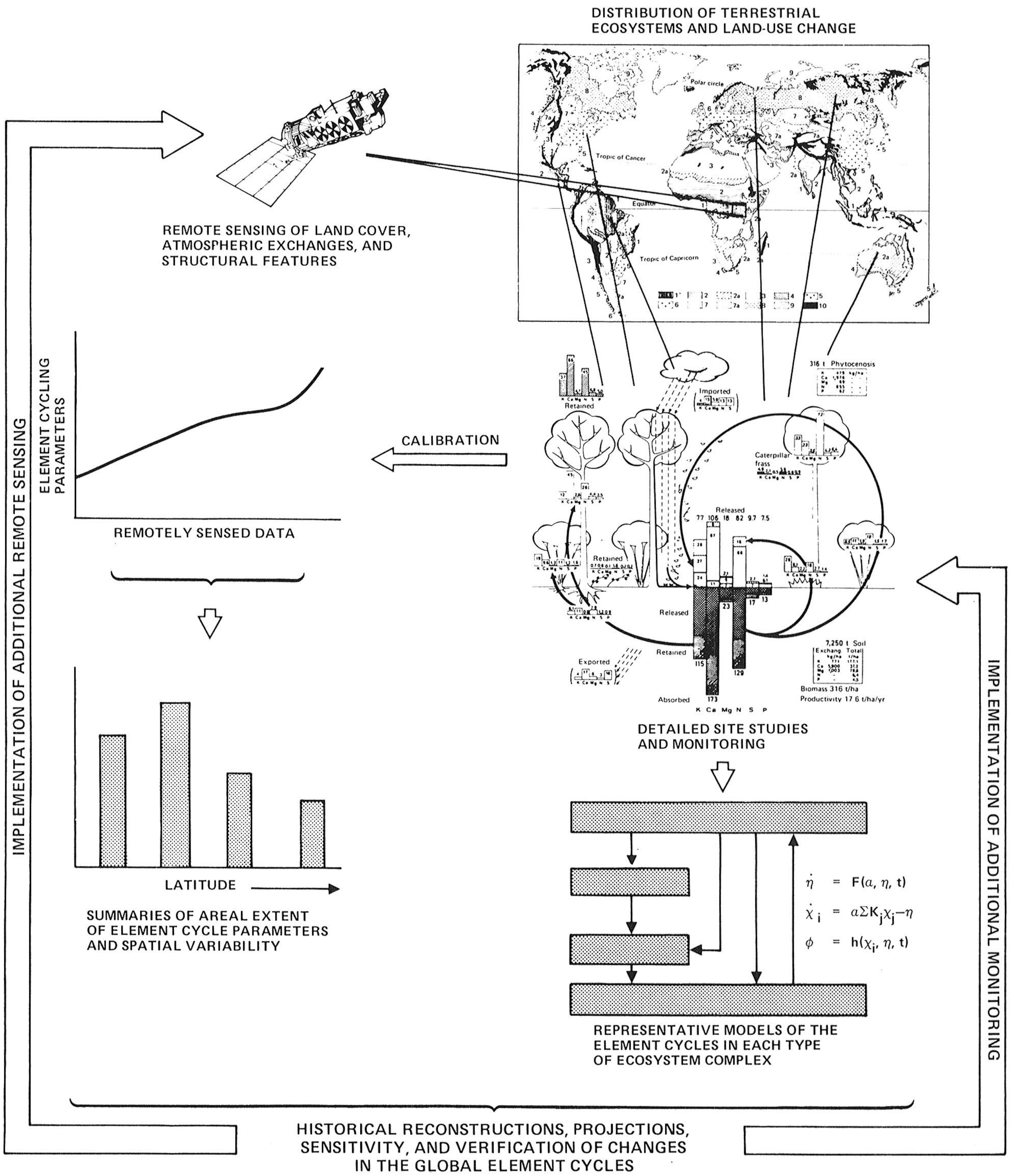


Figure 7 - Relationship of Biogeochemical Cycling Research Areas

formulating hypotheses, and developing monitoring plans. As the program matures, NASA-funded study sites will be implemented and, through joint efforts, monitoring at other sites intensified.

Instrumentation for monitoring the element cycles in terrestrial ecosystems will be improved by this research program. Particular emphasis will be on development and use of instruments to measure the composition of fluxes associated with microbial activity in the litter and soil. Soil microbial activity can be most readily monitored by following changes in the concentrations of volatile components. Small gas liquid chromatographs which analyze samples from various soil horizons collected through teflon capillaries developed under existing support by staff at the NASA-Ames Research Center is an example of the required technology. Such devices might be deployed on a grid over substantial areas to provide the detailed chemical analysis necessary for a satisfactory description of the element cycles. The evasion of some gases to the atmosphere from terrestrial ecosystems can be measured with airborne sensors. This approach will be exploited where realistic.

The applicability of remote sensing from space in the study of the global element cycles limited with present technology because, as previously discussed, crucial aspects of the terrestrial element cycles occur in the soil and depend on the function of microorganisms in litter and soil. A long-range goal of this program is to discover methods to remotely sense even these obscured variables. The landscape pattern in the terrestrial element cycles will also be explored by developing models or transfer functions which express the relationships between variables which can be remotely sensed, such as land-cover or climate and the characteristics of soils and the element cycles. Data remotely sensed from space will be compared with ground data from intensively monitored sites to develop such transfer functions. In most instances, the required relationships will likely not be obvious, and theoretical constructs will be used to form the necessary framework.

Spatial Variability in the Terrestrial Element Cycles

There is substantial variability in the dynamics of the element cycles even across regions of similar ecology, and a complete theory relating this heterogeneity to variations in the factors which dictate the character of the cycles is essential to the development of reliable global models. Satisfactory characterization of spatial variability in the terrestrial element cycles is a major theme of this research.

The dependence of ecosystem properties on controlling factors can be simply expressed as functions of the form (1) $c = f(x1, x2,\ldots,xn,t)$ where c is a particular property or variable; the x(1), x(2), etc., are controlling factors; and t reflects a dependence on time. In soil science, this approach has been called the "factor function paradigm" (Jenny, 1941). In the case of soils, c is a property such as organic carbon density, and the factors x(1), x(2), etc., include climate, parent material, and vegetation. This research will begin to treat the factors x(1), x(2), etc., as random variables, and functions such as (1) will become probability distributions.

Measurements collected at various sites can be sorted according to ecosystem type, and the variance in these data can be analyzed by standard statistical methods to derive functions in the form of (1) applicable to particular types of ecosystems or regions. Further, data from a number of ecosystem types can be compared with environmental factors such as climate to deduce even global scale patterns. The relationships between soil carbon density and climate have been demonstrated using Holdridge's Life-Zone System at the global scale (Post et al., 1982). These types of synthesis will be particularly important during the initial years of this research program.

As research progresses, a spatial dimension will be added to the factor function description of the terrestrial element cycles. Three components are required: (1) the factor functions for each major ecosystem type just discussed; (2) the functions relating important element cycle characteristics to variables which can be remotely sensed as discussed in the previous section; and (3) remotely sensed data for ecological (land-cover, productivity, etc.) and environmental (climate, topography, etc.) variables. By integrating remote sensing information, the factor functions (1) can be treated as extending across regions of applicability, and the properties of the element cycles at a particular place can be estimated by evaluating the appropriate functions. A particularly important aspect of this approach is that the spatial aspect of the factor functions can be updated as additional remote sensing data is retrieved. This continual updating will reflect not only improved information in the sense of more samples, but also the actual changes which occur as a result of disturbance such as land-use change.

Dynamics of the Element Cycles at the Ecosystem Level

The relationships between properties of the terrestrial element cycles and controlling factors, such as climate, when coupled with systematic data sets collected from representative sites provide the basis for understanding the dynamics of the element cycles in each of the world's major ecosystem types. This synthesis, primarily a collection of mathematical models, will constitute a major product from this program's efforts to further understanding of the terrestrial element cycles.

Compartment models of each element cycle will be developed for the world's major ecosystem types. In addition to the major elements carbon, nitrogen, sulfur, and phosphorus, other elements and trace substances will be modeled for particular ecosystem types. Both living and dead components of each ecosystem type will be considered, and appropriate representations will be included to permit simulation of the response of the cycles to disturbance. Interactions among the cycles and dependence on environmental factors such as climate will be emphasized.

Calibration of compartment models for the element cycles requires some indication of the turnover times for each pool. Turnover times can frequently be indirectly estimated, but only in a few cases are direct measurements available. Data collected at particular field sites in conjunction with this research program should include better information in this regard. A key improvement to be exploited by this program is the tracers for the elements of interest. Radioisotopes are particularly useful for determining transit time

and age distributions for various pools. Other tracers such as (13)C and (15)N may indicate the sources and sinks with respect to a compartment. Tracer-based methods, such as the inverse method based on singular value decomposition, will be used to estimate model parameters from available tracer data.

The collection of models of the element cycles in terrestrial ecosystems will be constructed such that appropriate models can be adjusted to simulate the element cycles in the type of ecosystem for which they are intended in any region of interest. This facility makes possible coupling of this set of compartment models with land-cover data derived from remote sensing and other sources to global scale dynamics. Two features of the models will make this flexibility possible:

1. The detailed relations between controlling factors and properties of the element cycles included in the models will provide the necessary coupling with climate and other environmental factors.

2. Explicit treatment of spatial variability by allowing parameters in the models to be random variables when appropriate will avoid the unsatisfactory use of mean values across large landscapes.

Land Cover and the Terrestrial Element Cycles

Land-cover maps and tabulations derived from remote sensing data are fundamental to studying the spatial aspects of the global element cycles. Changes in land-use and land management practices impose perturbations or temporal shifts in the major element cycles which complicate our understanding of their basic dynamic character. Methods will be developed to investigate these changes with satisfactory spatial detail. By combining the ecosystem level models of the element cycles discussed above with land-cover classifications and maps depicting the areal extent of regions of applicability, simulations of large-scale changes in the cycles will be obtained. The requirements for land-cover maps in global element cycling research are met by the work described in more detail in the Land Cover section of this report.

Documentation of land-use change prior to early satellite remote sensing in the 1970s relies on several types of historical data and statistics, including: (1) vegetation and land-use maps; (2) agricultural and forestry production statistics such as those published in the FAO yearbooks; (3) areal photographs; and (4) demographic and economic data such as census and tax records. During early stages of this research program, these data will be assembled and analyzed to reconstruct land-use change as it bears on the biogeochemical cycles from a period of essentially natural land cover to the beginning of the remote sensing record. This effort will begin with the recently published synthesis of Houghton et al. (1982).

Beginning with the early satellite remote sensing programs, land-cover summaries become more reliable. These data will be used to derive maps of land-cover at several key points in time in addition to a detailed mapping of current conditions. An initial priority is to estimate cumulative change in

properties of the global element cycles by comparing contemporary land-cover conditions with maps of natural conditions derived from climate and other environmental factors.

Projecting Changes in the Terrestrial Element Cycles

Historical changes in major element cycles due to disturbance by land-use change, and introduction of trace compounds and modifications to their dynamics, will be documented as a bridge from the natural conditions to those of the contemporary landscape. This reconstruction of the biogeochemical cycles provides a synthesis and testing of understanding of the cycles, and is a basis for projections.

Reconstruction of the cycles is accomplished by simulating dynamics with coupled models typical of ecosystems in major regions, and integrating through maps of land-cover at various times. Over the last decade, these maps will be derived from remote sensing data. For earlier points in time, additional land-use data, correlations with population change, and natural landscape conditions inferred from climatic data may be used.

To the degree that changes in land-cover and the introduction of additional trace compounds can be projected, models, data base, and maps of land-cover will be used to project further modifications of the major element cycles and, in turn, biological productivity and world land habitability in general.

In planning a program of research to further our understanding of the global element cycles, the need for several kinds of instrumentation and remote sensing technology is obvious; however, current understanding of the global element cycles limits our ability to make a definitive statement as to the most important variables and properties for monitoring. A major goal of this research is to determine the monitoring program required to document further changes in the terrestrial element cycles in satisfactory detail. Sensitivity analysis and other simulation studies with the spatially detailed models developed by this program will indicate key variables and the appropriate methods and resolution for monitoring.

II.3.4 MEASUREMENT REQUIREMENTS

Terrestrial biogeochemical cycling research requires a coordinated combination of laboratory, ground, atmospheric, and remotely sensed data to explain phenomena and provide results to drive and verify models.

Laboratory work is required to clarify the basic processes responsible for element transformations and exchanges, and their dependence on environmental conditions. Required techniques include gas chromatography, radioisotope counting, mass spectrometry, chemical analyses, and biological essays. Measurements under controlled environmental conditions are necessary to establish relationships to climate, atmospheric composition, and soil chemistry. As work progresses, microcosm studies in environmental chambers with atmospheric as well as climate control will be required.

As previously indicated, intensive monitoring at field sites representative of each of the world's major terrestrial ecosystem types is necessary. At these sites, essentially all aspects of the biogeochemical element cycles must be quantified insofar as possible. Measurements will include chemical analyses of each pool, standard vegetation surveys, and water chemistries. Tracer methods using both stable and radioactive isotopes will be used to quantify fluxes and turnover rates. Whenever possible, field work will be conducted at existing sites where much of the instrumentation is already in place and baseline data has been collected. An early priority for this program will be to develop liaison with such sites and implement additional monitoring where necessary.

Field measurements will be required on soluble and volatile gas concentrations and their flux rates, key microclimatological variables such as air and soil temperatures, solar irradiation, humidity, precipitation, critical canopy structural variables such as leaf area and density, species composition, and important physiological variables such as net assimilation rate and total biomass by compartment. Some of these measurements require development of new instruments such as field-portable miniaturized gas chromatographs.

In order to close cycling budgets on large or small landscape units, atmospheric measurements will be required. High sensitivity and fast-response time measurements of trace compounds will be made using aircraft that can characterize the air mass vertically and horizontally at propitious times to capture the variability in cycling processes. Wet and dry deposition must be characterized by size distribution and composition. On a site basis, information about circulation, wind speed, and other climatic conditions is required.

Finally, remote sensing measurements will be necessary. Many desired measurements such as areal extent and spatial distribution of biomes, species composition, and structural features will eventually be forthcoming from other program elements. Also necessary are measurements of evapotranspiration, soil properties, soil moisture, and temperature. However, many unique remote sensing measurements are required to study the biogeochemical element cycles. To adequately capture the high spatial and temporal variations in some key processes, diurnal, daily, and 2-3 day repetitions will be necessary. Other processes require seasonal coverage. Initially, nadir-viewing sensors will be used, but various look angles are likely to be necessary to provide particular information about the soil surface and vegetation canopy.

Both passive and active devices are necessary. Passive devices will be needed in the visible and infared regions in both wide and narrow band configurations. For many ecosystems, these devices will yield useful information about vegetation composition, structure, and biochemical characteristics. Ultimately, active devices are necessary to detect gas chemistry at the soil and vegetation surfaces.

II.4 BIOLOGICAL PRODUCTIVITY OF THE LAND

II.4.1 INTRODUCTION

The Biological Productivity of the Land program element has the following scientific goals:

1. Provide an improved estimate of the net primary productivity and the standing biomass of terrestrial ecosystems;

2. Provide a better understanding of the interactions of all components affecting biological productivity (of globally representative terrestrial ecosystems);

3. Provide a basis of accurately predicting consequences of environmental stresses, human induced or natural, on the biological productivity of terrestrial biological systems;

4. Provide a basis for better management of terrestrial biological productivity.

Biological productivity is a function of many factors including climatic factors (temperature, precipitation), light received at the surface, the availability of major chemical elements required for life (carbon, sulfur, phosphorus, and nitrogen, etc.), and intrinsic properties of the biota. Since climate and the availability of nutrients can be affected in turn by the biota, we can write a general state equation:

$$F\{ B(i), R, T, W, C\ S\ N, P, NU(j)\} = 0$$

where B(i) is the i-th type of biota; R = radiation; T = temperature; W = water availability; C, N, S, and P, the macronutrients of primary interest; and, NU(j) = other chemical elements of interest.

The ultimate biological variable of interest is net primary productivity (NPP). The primary productivity of an ecological system may be defined as the rate at which energy is stored by photosynthetic and chemosynthetic activity of producer organisms (such as green plants in the form of organic substances).

Other major biological variables of interest are the leaf area index (LAI), which is the number of layers of leaves overlaying a unit of land area, the total biomass accumulation (TBA), and the rates of decomposition. Decomposition may be defined as the conversion of biomass to small inorganic compounds. Decomposition of dead organic biomass by the activity of microbiological organisms is important to the maintenance of ecosystems through the release of the nutrients stored. The relative magnitude of decomposition processes will change as the age of the ecosystem changes.

A generalized relationship amongst LAI, NPP, and TBA for a plant community is illustrated in Figure 8. Across biomes, these variables differ markedly in

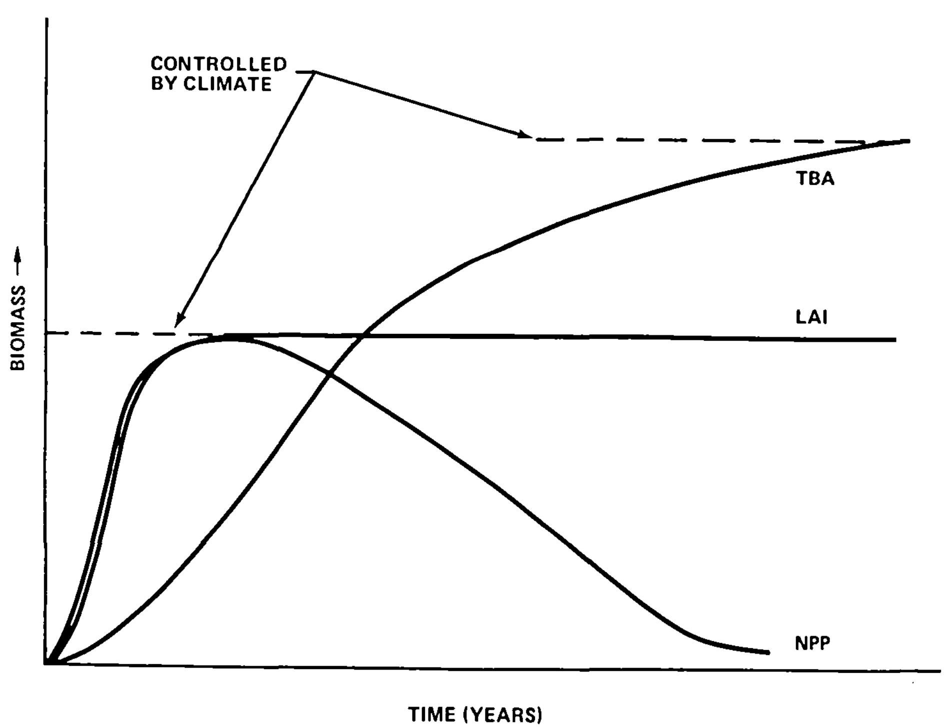


Figure 8 - Idealized Trends of the Development of a Terrestrial Plant Community Over Time. LAI = Leaf Area Index, NPP = Net Primary Productivity, TBA = Total Biomass Accumulation

absolute magnitude (Y axis) and in developmental timing (X axis). LAI can range between 0 and 23. NPP can vary by at least a factor of 100 from desert or tundra to forests; TBA varies by three orders of magnitude. The X axis time scale may be one year for an annual crop or temperate grassland, to 300 years for a temperate coniferous forest.

Each variable is critical for different components of global biogeochemical cycles. LAI provides the active surface for energy, water, and CO(2) exchange, and is the component most easily measured that correlates with NPP and TBA. NPP measures the annual energy captured and is important as a measure of products generated for society. TBA relates to total carbon storage and is proportional to biotic storage of other key elements (N, P, S, etc.). High correlations have been found amongst these variables. LAI, the photosynthetic factory, can be correlated with both NPP and TBA with r(2)> 0.9. LAI is best predicted by site climatic factors, or measured directly.

II.4.2 SCIENCE ISSUES AND THEIR IMPORTANCE

Methods of Measuring Net Primary Productivity and Biomass

Having set down the basic reasons to measure biological productivity and biomass to improve our understanding of biogeochemical cycles, energy and water budgets, and changes in land cover, it is essential that methods for measuring these factors be addressed. First, it is necessary to distinguish between potential and actual biomass. Potential biomass is the maximum that could exist in an area given the climate, geology, and topography. Actual biomass is the amount present at any time of observation. Similarly, potential productivity is the maximum productivity that could be obtained in a given climate, geology, and topography; actual productivity is the rate observed at any time.

Most existing estimates tend to be of potential biomass and productivity.

The Zeroth Approximation

The zeroth approximation is to determine the state of standing biomass at the present time. The zeroth approximation of biomass is calculated by multiplying site specific measurements of biomass per unit area for each biome by the estimated land cover of that biome. A biome is a class of ecosystems.

Table 3 summarizes the best current estimates of global NPP and TBA by biome. Our confidence in these estimates is no more than $\pm$ 50 percent. There is large uncertainty in the estimates of areal extent of each biome as well as in the extrapolation of point data to whole biomes.

The First Approximation

Extrapolation of productivity and biomass data can be improved by correlating NPP and TBA with environmental parameters. Collection of routine climate data (temperatures, precipitation) is much more widespread, and ground based weather station data has been compiled on a global basis by groups such as the World Meteorological Organization (WMO). Results from this type of analysis

TYPE	AREA (10^8 KM^2)	TOTAL NET PRODUCTION (10^4 TON^3/YEAR)	TOTAL BIOMASS (10^4 TONS)
TROPICAL RAIN FOREST	17.0	15.3	340
TROPICAL SEASONAL FOREST	7.5	5.1	120
TEMPERATE FOREST, EVERGREEN	5.0	2.9	80
TEMPERATE FOREST, DECIDUOUS	7.0	3.8	95
BOREAL FOREST	12.0	4.3	108
SUBTOTALS (FORESTS)	48.5	31.4	743
WOODLAND AND SHRUBLAND, SAVANNA	23.0	6.9	49
TEMPERATE GRASSLAND	9.0	2.0	6.3
TUNDRA AND ALPINE	8.0	0.5	2.4
DESERT AND SEMIDESERT	18.0	0.6	5.4
EXTREME DESERT, ROCK, ICE, SAND	24.0	0.04	0.2
CULTIVATED LAND	14.0	4.1	7.0
SWAMP AND MARSH	2.0	2.2	13.6
LAKE AND STREAM	2.5	0.6	0.02
TOTALS	149.0	48.3	827

Table 3 - Net Primary Production and Biomass of Land Biota

are shown in Figure 9. This impressive looking map was generated from a single equation:

$$NPP = 3000\{ 1 - \exp(-0.00097(AET-20))\}$$

using 1125 points of yearly actual evapotranspiration (AET) data and 52 data points of NPP from different biomes worldwide.

<u>The Second Approximation</u>

A more direct method of assessing primary productivity in some biomes is by measuring leaf area index (LAI) of plant canopies. LAI is expressed as layers of leaf area per unit land area (square meters of leaves/square meters of land surface). Research has shown that water exchange and carbon dioxide exchange by vegetation is linearly correlated with LAI, at least within a range of two to seven. Recent analysis of NPP data from International Biological Program (IBP) sites across the United States are given in Figure 10. A high correlation was found between foliar standing crop (analagous to LAI) and NPP from 30 sites across four biomes.

Remote sensing experiments, like LACIE and AgRISTARS, have suggested that leaf area indices within the range of two to seven for agricultural crops and grasslands can be measured from aircraft and satellite sensing platforms. Initial tests to measure LAI in forests from Landsat-D imagery are in progress. Thus, it is possible to specify a measure of the short-term activity of vegetation, and indirectly, vegetation-atmosphere interchange from remote sensing. From LAI, biome type and region, one could derive equations to be used to predict primary productivity of sampled ecosystems. It should be emphasized that net primary productivity (NPP) is considered a key process in terrestrial ecosystems. Exchanges of energy, matter, and water between the atmosphere and the biosphere will be proportional to LAI and net primary productivity.

The Achilles heel of the zeroth and first approximations of global NPP is the inaccuracy in extrapolating point-source data of measured NPP to large areas. Remote sensing of LAI can provide a measured quantitative vehicle for these extrapolations that could improve the estimates in Table 3 significantly. Depending on the classification level and spatial resolution desired, measurements could be taken at a number of different levels. (Figure 11).

However, LAI is not a sufficient measure, in itself, of plant ecosystem dynamics. The LAI of a western coniferous forest, for example, may peak at a stand age of 30 years, while biomass will continue to accumulate for 200 years. Consequently, any measure of LAI alone will not provide a measure of standing or maximum biomass. Many vegetative crops develop significant NPP through fruit development that is, in turn, not particularly well-correlated to LAI. Grasslands and croplands cycle annually between zero and maximum living leaf area.

The time interval for measurements varies with biome and structural state of the vegetation. In some biomes, maximum LAI may be reattained within five

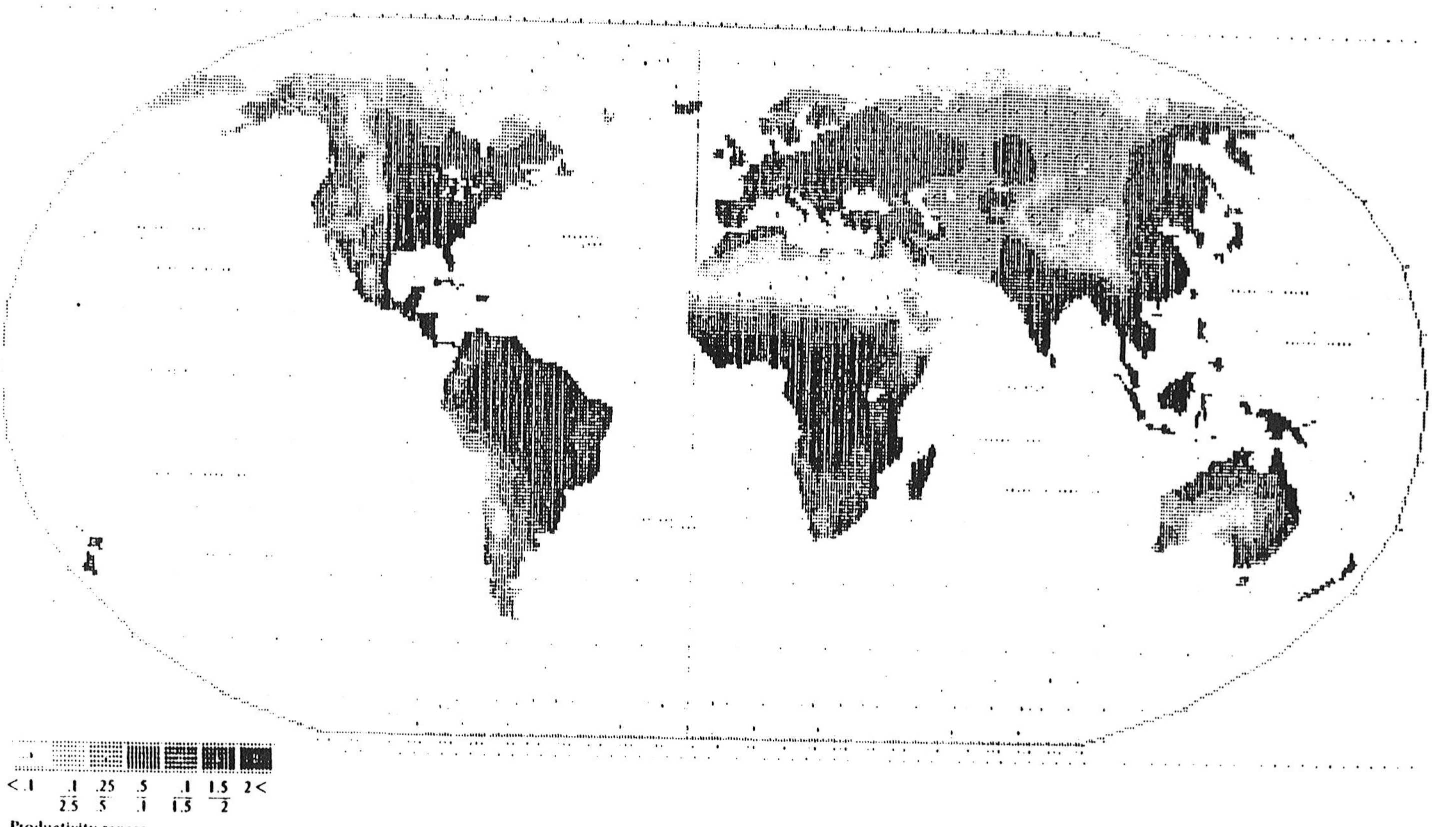


Figure 9 - Primary Productivity of the World Predicted from Actual Evapotranspiration

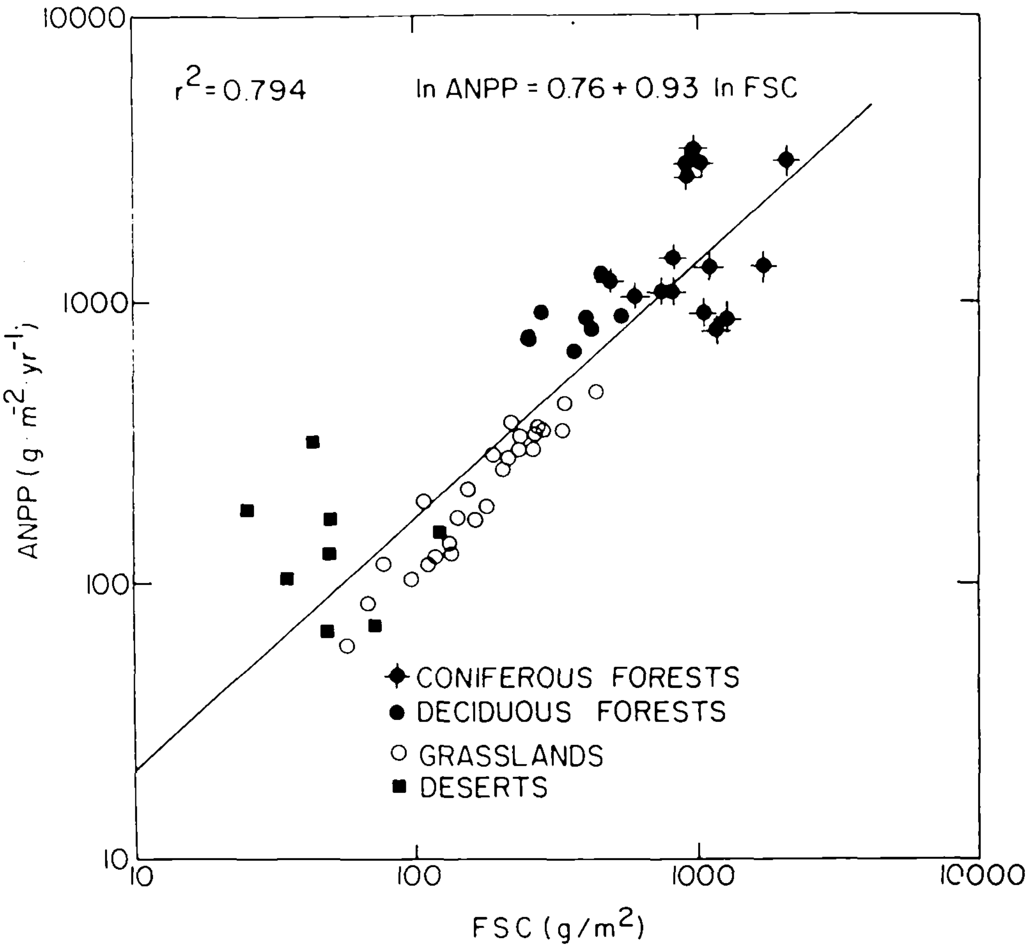


Figure 10 - Relationship Between Aboveground Net Primary Production (ANPP) and Peak Foliar Standing Crop (FSC) of Forests, Grasslands, and Desert Sites.

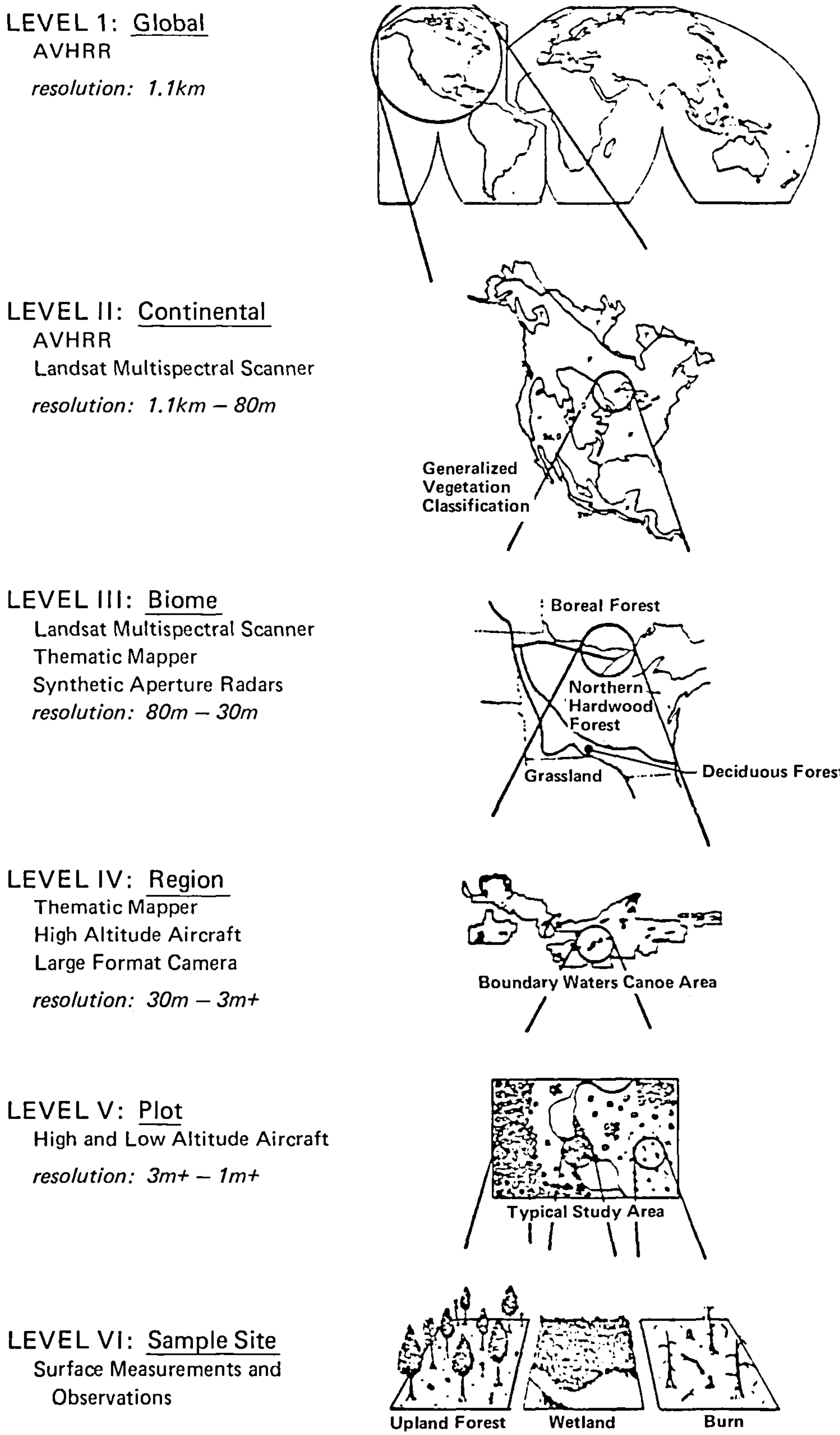


Figure 11 - Relation of Classification Level and Spatial Resolution

years of disturbance. Over this short time-frame, maximum LAI could be observed by annual measurement until equilibrium is reached. On sites with a longer recovery time, maximum LAI may have to be predicted from climatological analysis of the specific area. However, this may be difficult on a global basis. Maximum LAI and other structural variables may be limited by light, water, temperature, nutrients, or some combination of any or all four basic driving variables on any given site.

The primary factor limiting productivity and biomass varies among biomes and, to some extent, within biomes. For example, in the arid western United States, a site water balance can be used to predict maximum LAI and net primary productivity. In the moist, warm tropics, light penetration through multiple layers of canopy may ultimately limit LAI. Particularly in cold boreal climates, temperature limits vegetation development, decomposition, and LAI. There is also a complex relationship between nutrient and water availability. Plant geographers have had the most success in relating plant distribution to water and temperature regimes. However, nutrient cycling research is demonstrating that linkages exist between nutrient levels and decomposition rates controlled by temperature and water regimes, which can regulate the rates and efficiency of primary productivity.

Thus, it is often useful and important to estimate actual and potential biomass and productivity. This allows us to compare the maximum and current biotic storage of chemical elements and the maximum and current flux of these elements. Disturbances, both human and natural, reduce biomass and LAI below the potential.

A more difficult but potentially valuable addition to LAI and biomass data would be detection of biochemical characteristics of canopy leaves. This can be done by "signatures" of reflectance or emissivity of several wavelengths. Significantly, different signatures from different parts of the same biome could be correlated with the presence of different species or physiological states of leaves--a key factor in determining the rate of decomposition and nutrient cycling.

In summary, for the second approximation, knowledge is needed of:

1. The present leaf area index;

2. The maximum LAI a site will support based on limitations of light, temperature, water, nutrients;

3. The temporal relationship between present and maximum LAI, and maximum biomass;

4. The absolute and temporal relationship between maximum LAI and maximum biomass, and

5. The present biomass.

We feel that only remote sensing can provide this data on a scale appropriate to global studies.

The Next Approximation

We envision a model of global primary productivity that would rely on a synthesis of remote sensing data, biome-specific computer simulation models, and ground based measurements. This model would integrate the results of the other science elements in energy balances, hydrologic cycles, biogeochemical cycles, and land inventory into a high resolution estimate of global productivity and biomass. The global model would be sufficiently mechanistic to provide defensible scenarios to the questions of global consequences of atmospheric CO_2 augmentation, tropical deforestation, acid rain, etc.

1. Develop a biome classification scheme and conduct a global land cover inventory that would be repeatable, to assess disturbance, frequency and permanent cover changes. This is being designed in Section II.5.

2. Organize the appropriate sensors to provide regular measurement of near-surface temperatures, shortwave radiation balance, and surface water balances. These tasks are outlined in Section II.1 and II.2. The temporal and spatial resolution of these measurements will be dictated at least in part by the needs of the computer models in step 4.

3. Conduct global measurement by satellite of leaf area index and current plant biomass for each biome.

4. Develop process-level computer models of NPP specific to the vegetation in each biome. These models would calculate photosythesis-respiration, elemental cycles, carbon allocation, and decomposition. The biome-level models would be aggregated into a global model. Sensitivity analysis of the global model would allow judgement of the relative importance of potential biosphere perturbations.

5. Drive the models in step 4 with near real-time satellite measurement of surface climate from step 2, and land surface changes from steps 1 and 3. These models could be self-correcting with measured NPP, LAI and TBA from step 3.

This general scenario is depicted in Figure 12. A proposed coupling amongst the satellite data base, computer simulation process modeling and terrestrial ecosystem models, is illustrated in Figure 13. It is quite clear that each biome will require individualized process and ecosystem models. A grassland does not partition carbon the same way as a coniferous forest. It is less clear if these generalized process models can treat within-biome variability adequately. Validation of a model framework such as this also will require significant field data collection. Finally, the use of meteorological satellite data for driving these models requires a new look at the capabilities and data reduction systems used with the meteorological satellites. It should be emphasized that we see this as an end product of a Global Habitability Program. The research objectives in each element of this science plan outline intermediate research tasks necessary to achieve this goal.

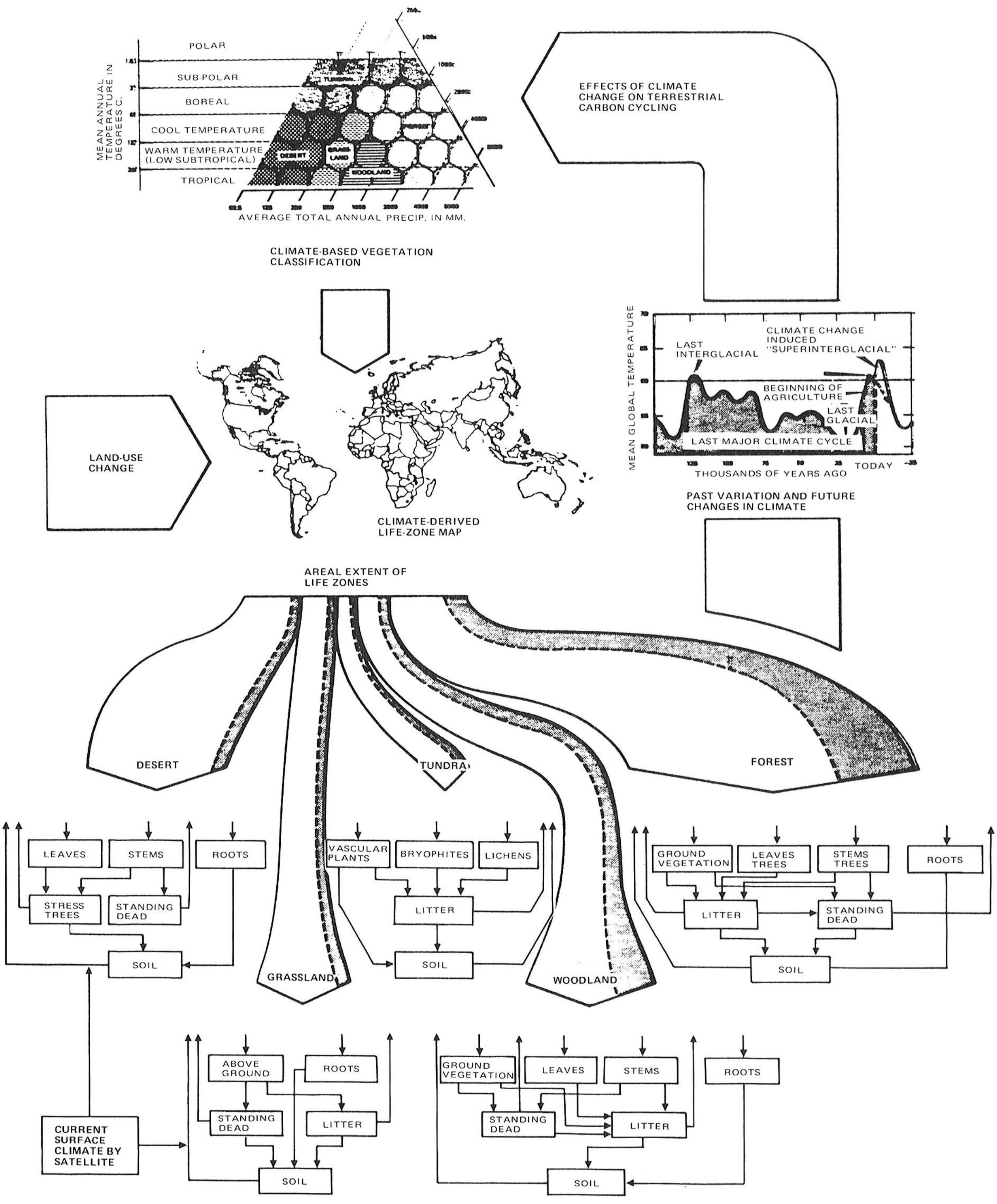


Figure 12 - Biome Classification for Ecosystem Modeling

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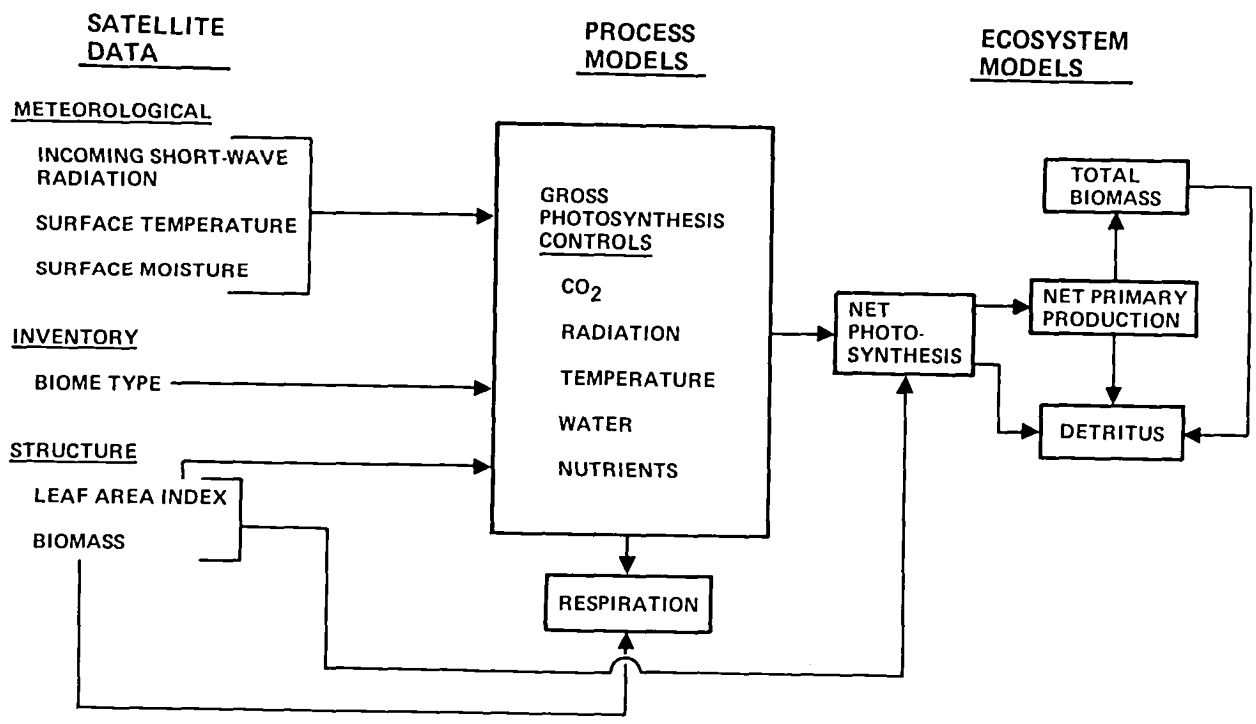

Figure 13 - Ecosystem Models Using Satellite Data

II.4.3 RESEARCH AREAS

The general objective of the Biological Productivity element of the program is to improve understanding and modeling of the spatial distribution and temporal dynamics of biological productivity in terrestrial ecosystems.

The specific research objectives are:

1. Assess the areal extent and spatial distribution of biomass and net primary productivity of the major biomes.

2. Improve the accuracy of estimates of structural variables (such as leaf area index, etc.), total biomass and actual net primary productivity of terrestrial vegetation and relate these to environmental driving forces.

3. Establish the potential biological productivity and the factors controlling this potential productivity (soil, topography, nutrients, water, temperature, pollutants, sunlight, etc.).

4. Establish the rates of decomposition and determine the factors controlling these rates.

5. Determine the extent to which changes (both positive and negative) could be initiated in the productivity of major biomes.

Specific comments on research objectives follow but are not considered exhaustive of intended research.

Objective 1: Assess the areal extent and spatial distribution of biomass and net primary productivty of the major biomes

A. Determine criteria for identifying and distinguishing biomes:

(1) The kinds of criteria for identifying actual biomes:

(a) major species
(b) macrostructure of vegetation (physiognomy)
(c) levels of NPP and biomass

(2) The kinds of criteria for identifing potential biomes:

(a) Estimate from climate, topography, soils, and geology

B. Determine criteria for establishing transitions between biomes:

(1) Criteria for determining transitions are:

(a) Transitions between species composition
(b) Transitions between physiognomic types
(c) Transitions between levels of NPP and biomass
(d) Transitions of climate, soils, topography, and geology

(2) This is an empirical (_a posteriori_) issue, not an _a priori_ issue. As such, it becomes an operational issue. (Caveat: Although there may be one classification scheme devised at the outset, it is likely that several slightly different criteria will emerge as useful for different issues. For example, the classification scheme chosen to be descriptive of the nitrogen cycle may be slightly different from that chosen for energy budget calculations.)

C. Criteria for choosing initial biomes for study:

(1) Choose those with large biomass or NPP, or important in the flux of major biogeochemical cycles

(2) Choose biomes undergoing rapid change

(3) Choose biomes in which successful measurements are most likely--i.e., those with

a. good cloud free periods
b. accessibility for ground verification

D. Exploratory research utilizing satellite measurements needs to be conducted to compare actual type, amount, and extent of production/productivity in selected biomes to existing estimates available from other sources.

(1) Consideration should be given to the regions having relatively uniform characteristics as well as those having important "within region" variations.

(2) Regions should be selected for which apparently credible estimations already exist, and for which adequate Landsat (and other) data exists.

E. In addition, research is needed to utilize satellite data together with those from in situ measurements to establish estimates of known precision for critical vegetation characteristics in important biomes.

(1) Initial research should concentrate in important photosynthesis producing biomes and in a succession based on degrees of difficulty.

(2) Emphasis should be given to optimal joint use of data from multiple sources.

(3) Emphasis should be given to establishing estimates of bias and precision for more promising approaches.

Objective 2: _Improve the accuracy of estimates of structural variables, total biomass, and net actual primary productivity of terrestrial vegetation and relate these to environmental driving forces._

A. Determine the kind of canopy structural variables expected to be related to net primary productivity and total biomass for different biomes:

(1) leaf area and leaf area index
(2) canopy height
(3) stand or stem density
(4) age
(5) phenology
(6) basal area or stem diameter

B. Develop plant canopy models for predicting spectral radiance characteristics for selected portions of the electromagnetic spectrum for various plant communities. Criteria may be:

(1) plant morphology
(2) leaf, branch, bole radiative properties
(3) leaf, branch, bole physical properties
(4) phenological characteristics
(5) stature and spatial arrangement

C. Develop improved and efficient techniques for characterizing biomes in situ using nondestructive measurement techniques.

D. Explore the remote sensing capability to estimate structural variables using existing satellite and aircraft sensors:

(1) optical wideband and high spectral resolution radiometry
(2) active sensors and scatterometry
(3) high and low spatial resolution radiometers
(4) thermal infrared sensing
(5) variations of look angle/sun angle combinations

E. Explore the capability of sensors, alone or acting together, to describe the spatial distribution of structural variables for biomes.

F. Develop correlations of known precision between measured structural variables and net primary productivity and total biomass for important selected biomes as defined in Objective 1. For example, leaf area index integrated over the growing season is positively correlated with net primary productivity of green biomass in grasslands.

G. Abiotic control of LAI, other structural variables, NPP, and biomass accumulation can be approached at two levels:

(1) Using empirical relationships between global correlations of actual evapotranspiration and/or precipitation/temperature regimes with net primary productivity.

(2) Biome specific correlation models -- semimechanistic models predicting NPP of different plant types as driven by water, temperature, radiation, and nutrient conditions. These models would be specific to the

physiology and phenology of the plant type (coniferous tree, grass, irrigated crops, etc.). The models would be developed to use remotely sensed driving variables, and current structural condition of the plant community, with monthly to annual temporal resolution.

Objective 3: Establish the potential biological productivity and the factors controlling this potential productivity

A. Compare: (1) existing maps of global productivity; (2) maps generated from "life-zones" (correlation of climatic variables with vegetation types); and (3) vegetation distribution maps derived from remote sensing data (as with AVHRR).

(1) Item (2) above involves the use of existing models that relate NPP to other variables. In terms of the state equation (Section II.4.1), we can write

$$dB/dt = f\{B(i), R, T, W, C, N, S, P, NU(j)\}$$

(2) Step A will be a first-order test of such a model(s). Results of Step A will imply developments required to improve the models and the data required to test them.

B. The procedure outlined in step A can be done at several levels of spatial resolution (see Figure I2). It is not clear now which resolution will be the most useful, most accurate, most easily verified, or provide the best estimate of statistical variation. Therefore, the procedure in Step A should be conducted using a suite of spatial scales and sensor devices.

C. Biome-specific process models:

Potential NPP can most rigorously be predicted from process models of photosynthesis, respiration, and transpiration specific to the physiology and phenology of the vegetation in each biome. These models would have higher temporal resolution (about one week or less) and not be constrained by current condition of the vegetation.

Objective 4: Establish the rates of decomposition and determine the factors controlling the rates

A. Develop the criteria for relating substrate quality (vegetation characteristics) and the temperature and moisture conditions (microbial populations) that influence decomposition rates of vegetation in different biomes.

B. Determine remote sensing variables that can differentiate the states of (various) plant communities that affect major decomposition processes such as:

(a) senescence
(b) decadence and age
(c) canopy closure (influences litter temperature)
(d) environmental stress and disturbance, large scale mortality induced by biotic agents

C. Explore diagnostic techniques which relate to decomposition, such as trace gases.

D. Relate decomposition rates to nutrient availablity and subsequent influence on NPP.

Objective 5: Determine the extent to which changes (both positive and negative) could be initiated in the productivity of major biomes

A. Use models to determine the capacity for increase. This requires results of Objective 2 (determinations of actual NPP and biomass) and Objective 3 (determinations of potential NPP and biomass). Models derived from Objective 3 can provide an estimate of the maximum productivity. The difference between Objective 2 and Objective 3 is the remaining capacity for increase.

B. Assess which controlling factors could be altered with the greatest effect. Criteria include:

(1) Which factors are open to control (can be controlled)?
(2) Which of those open to control provide the greatest effect for the least effort, e.g., is the atmospheric CO(2) still controllable? What will be the response of the vegetation?

C. Assess the likelihood by biome for decrease due to no-longer controllable changes in variables (such as acidification of rainfall).

D. Assess the actual rate of change of biomass and NPP of the major biomes.

(1) This requires a monitoring program based on Objective 2.

Priorities

First priority: Research Objectives 1, 2, and 3.

Second priority: Research Objective 4.

Third priority: Research Objective 5.

II.4.4 MEASUREMENT REQUIREMENTS

To conduct the research outlined in this program element, measurements will be required from in situ instrumentation, from aircraft platforms, and from satellite sensors already deployed or being planned, such as Shuttle experiments.

To estimate the variables identified (species composition, various structural properties, biochemical characteristics, decomposition properties), specific sites representative of major selected biomes, such as temperate and cold

climate forest, grasslands, savannah, crops, tropical forest, etc., must be instrumented and physically measured in space and time. This will require the development and testing of in situ non-destructive techniques to measure the structural properties of vegetation communities such as leaf area index, leaf biomass and its spatial distribution, leaf inclination angle distribution, leaf size distribution, canopy closure, bole diameter, branching pattern, stem density and its spatial arrangement, and basal area. The radiometric properties of the soil-litter-understory-overstory continuum must also be established. Laboratory measurements of the reflective-absorptive properties of canopy components, such as various age leaves, bark and stems for various conditions of vigor and stress, will be required. Consideration must be given for both the living and dead biomass on the site. In situ instruments to measure the rate of photosynthesis, respiration, evapotranspiration, and other biological processes would be highly desirable, including the rate of decomposition. These sites should be carefully measured for their radiometric properties, considering bidirectional effects and high spectral resolution, throughout and above the canopy. Both field-portable and boom-mounted radiometers will be required, and measurements acquired in the visible, near infrared, middle infrared, thermal infrared, and microwave regions of the electromagnetic spectrum. Finally, the vegetation composition and its state of vigor must be completely determined. Depending upon the phenological characteristics of the biome under study, many of these measurements may be required at different intervals throughout the growing season. Also, depending upon the developmental status of the biome, these measurements may be required for several years as a function of the phenomenon under study. These measurements are crucial to calibrate and verify the performance of plant canopy radiance models, and to evaluate the effects of atmosphere distortions to radiance values. Emphasis should be placed on obtaining measurements for which the precision and spatial/temporal variance can be explained.

This program element will be concerned with establishing present and potential vegetation and its relationship to environmental-driving variables. As described in the previous discussion of the science issues, the linkages to the other program elements will be utilized as much as possible to gather information on these environmental variables. Additional measurements will probably be required in situ. Existing records of abiotic variables can also be used for this, including the use of established research sites for which extensive data collection has already been accomplished. Typical measurements are: topography (elevation, slope gradient, aspect and slope curvature), soil properties, temperature profile and history both in the soil and the air mass, soil and plant water potential, precipitation pattern and history, disturbance events and history, geologic variables, and nutrient conditions including macronutrients, minor nutrients, and toxic substances. Many of these properties will be measured remotely using aircraft and satellite instruments, thus, these site specific measurements will be important to test the adequacy, precision, and sensitivity of these data. Existing climatological and digital terrain data/models will be evaluated for these studies. Microbial populations and decomposition processes may be characterized by laboratory analysis as well as through gas sampling in the field.

The quantitative estimation of LAI, total biomass accumulation, species distribution, and net primary productivity will require a combination of both passive and active sensing systems, perhaps operating in a multistage framework. For some biomes, LAI may be accurately sensed using passive sensors solely, such as the Landsat MSS, Thematic Mapper, Advanced Very High Resolution Radiometer (AVHRR). Research will be carried out to compare the relative performance and information content of these systems and their data density, varying in resolution from 30 meters to 1000 meters and in spectral waveband configuration between 0.45 and 12.5 microns. Airborne scanners can collect finer spectral resolution (Thermal Infrared Imaging System, Airborne Imaging Spectrometer, and Daedulus Scanner). Additional data may also be required from SPOT (20-meter spatial resolution), the Japanese LOS (Land Observing Satellite), from NOAA GOES, and the Shuttle's Large Format Camera. Frequent coverage of selected biomes will be required throughout the growing season, especially for vegetation displaying distinct phenological properties. Cloud free, polar orbiting, sun-synchronous, high sun angle data is the primary data source expected. However, nadir and off-nadir viewing angles and variable solar zenith angles may be desirable for exploring the potential benefit and/or problems associated with bidirectional reflectance and non-Lambertian effects. Data acquired at different times of day may also be advantageous. These data will require the removal of atmospheric effects and differential illumination induced by terrain relief. Registration problems must be overcome between sensor data sets and specific mapping surfaces, especially to correlate with abiotic information.

The precise estimation of biomass will require the utilization of active sensors, in some cases in combination with passive sensor data as described above. For ecosystems of tall stature, such as forests and brushland, active microwave sensing at wavelengths from 1 mm to 100 cm, multifrequency (X,L,C and K bands), various-look angles, and dual polarization will be required. Research to relate the backscattering response to the biophysical measurements on a site-specific basis as described above will be carried out. Some sensors which may be used in these determinations operate currently on either aircraft or spacecraft platforms including scatterometers, LIDAR, Shuttle Imaging Radar (SIR-A, SIR-B), SEASAT SAR, and Laser APR. Variables to be measured include canopy height, canopy closure, bole diameter, stand basal area, branching pattern, stem density, and vertical/horizontal arrangements. These sensors may be essential for cloud-prone areas, and have to be acquired seasonally. Aircraft and satellite measurement of climatological variables will also be required to test and validate models of potential NPP and biomass.

II.5 LAND SURFACE INVENTORY, MONITORING, AND MODELING

II.5.1 INTRODUCTION

The objective of this portion of the Land-Related Global Habitability Science Plan is to improve understanding of the spatial distribution and temporal dynamics of the global land surface. Knowledge gained will increase our understanding of land capability which can lead to improved insights concerning biological productivity and life support cycles. As used here, the term "land surface" includes geomorphology, lithology, soils, and other surface features in addition to general land cover; however, the term "land cover" will also be used frequently in this section to indicate a combination of vegetation, soil or rock, water, snow, ice, and cultural features. For the purposes of this document, land capability relates to the ability of the land to support and sustain a given surface cover.

The ability to accurately identify and classify those features and processes of the land surface which impact habitability is central to all land-related research. This is particularly true as we attempt to improve our understanding of the dynamic interactions which influence the long-term capability of the earth to support life. Different land cover types represent both a source and a sink of important constituents of the atmosphere, but the size, location, and temporal stability of these sources and sinks are essentially unknown. Critical parameters in climate studies can only be approximated until a determination of the albedo of the Earth's surface can be made. This requires that more precise determination of cover types be accomplished. Remotely sensed data has been widely employed in land surface mapping for inventory and, to a lesser extent, monitoring purposes in many areas of the world. The first large scale use of aerial photography for land cover mapping was the Tennessee Valley Project in the United States in the 1930's. Yet, at present, even in the U.S. there is no comprehensive, systematic assessment or monitoring of land surface information on a national, let alone a global scale. This is not to say that scientists have not recognized the need for such data nor that they have not been working to achieve a capability for global surface cover inventory, monitoring, and modeling. Considerable research is still needed, however, to accomplish such a capability. Important land surface research areas include the development of a remote sensing compatible set of hierarchical surface feature classification schemes; and, the improvement of: global surface cover inventory and monitoring techniques, models for describing and predicting surface feature dynamics, multistage sampling strategies, processing algorithms methodologies, and integration of remotely sensed data with other data types in geo-referenced data bases.

Major changes to the Earth's land cover are taking place due to natural processes, human use of technology, and as a result of population growth. These changes affect climate and the cycling of nutrients which may, in turn, affect primary productivity. Yet, there is little reliable information on the location and rates of these changes. Currently, we are unable to discern whether many of the changes we observe are due to natural processes or to human factors. This is, in part, the result of our lack of information and

understanding of the natural variations that occur. Seasonal changes in surface cover characteristics, and normal year-to-year variations in weather and plant community dynamics (including succession) cause changes in land surface cover features and, accordingly, surface reflectance characteristics. Models that utilize remote sensing and other data to depict actual vegetation or surface cover phenologies and dynamics are needed. The improved information on the rate and type of land surface cover alteration which could result from such models is necessary for a better understanding of biogeochemical cycling.

To date, analysis of biogeochemical cycles has placed a strong emphasis on the use of theoretical models. This has been forced upon researchers by a combination of the complexity of the biosphere and by our lack of data. Past models have primarily been driven by this combination of circumstances to represent static budgets and assume linear flux rates between major compartments. Such models are, by their very nature, unstable and typically move away, unless forced, from steady-state when solved by computer simulation. These models, in essence, represent a non-self-sustaining Earth and are basically unrealistic. It is difficult for such models to yield non-trivial hypotheses which can be adequately tested and verified. Remote sensing from aircraft and satellite platforms can provide the basis for much more realistic models. Models are also needed that can integrate remotely sensed data, site information, and climatic data, and predict the potential vegetation that would occur at a given site. Such models will improve our understanding of the impacts of a variety of environmental parameters on potential productivity and ecosystem stability. Finally, modeling is required that will forecast human impacts on surface cover. This effort should benefit from a systems approach to land surface cover model development.

The science issues discussed herein must be addressed by a closely coordinated research program. Such a program must involve the use of very large spatial data bases. The program will also require improved sampling and processing techniques, and the development of an advanced modeling capability which effectively employs the full potential of remotely sensed data. This potential offers, for the first time, a globally consistent data set from which estimates of the accuracy of knowledge of surface cover features can be derived. This information, once known, will facilitate our attempts to improve our understanding of the variety of dynamic interactions which impact global habitability.

II.5.2 SCIENCE ISSUES AND THEIR IMPORTANCE

Improvement of our understanding of the capability of the land to sustain those fundamental processes affecting the habitability of the Earth is the central science issue addressed in this document. Information on the location, areal extent, type, and rate of change of surface cover is fundamental to, and supportive of, an understanding of biogeochemical cycling, and to changes in the Earth's energy budget, and therefore to an understanding of climate dynamics. Different types of surface cover can have vastly different effects on the rates and magnitudes of cycling, yet we know little about the spatial dimensions and temporal stability of major surface cover features. The forests of the world represent a substantial organic carbon

reservoir; yet, worldwide estimates of the areas covered by forests vary in published sources by more than 100 percent. Estimates of land currently in agriculture in the United States vary by as much as 50 percent. Within the State of California, estimates on the yearly loss of primary agricultural lands range from as little as approximately 2,000 hectares per year to as much as 50,000 hectares per year. Remotely sensed data has already demonstrated its potential for producing statistical information on a variety of resource parameters, and is being employed as a base for mapping, also.

Most vegetation maps at regional-scales or larger produced by conventional methods are maps of the potential vegetation--what would be there without disturbance for a given climate, soil, etc. Such maps provide some useful information, but they are typically flawed by a lack of basic data and an imperfect understanding of the complex interactions which sustain vegetative growth and will over time produce the highest level of biological productivity. As such, these maps often contain little information concerning those processes important to long-term habitability. The fact is that these maps, indeed any map, represent a static image of a given area. As such, existing surface cover maps are inherently inaccurate. The accuracy, then, of many currently accepted surface cover maps at state, regional, national, continental, and global scales is highly suspect. Such maps are typically produced from a variety of input data compiled over very different time periods whose accuracies are almost never known to any degree of certainty. They represent the best efforts of researchers and cartographers to generalize extremely complex data into a format wherein meaningful information can be transmitted to a user on a given subject.

Current research on representational accuracy is directed towards comparing the land cover boundaries depicted on major cover type classification maps, such as those produced by the United Nations Educational, Scientific, and Cultural Organization (UNESCO), with boundaries derived from the analysis of Landsat multispectral scanner data. This and other research is demonstrating that data from Landsat and other satellite and aircraft remote sensing systems can be used to update and augment thematic information (e.g., soils, vegetation, land use, hydrology, geology, etc.) derived and represented in cartographic form from traditional sources. Indeed, satellite remote sensors offer the potential, essentially for the first time, for the generation of globally consistent input data sets from which the absolute accuracy of derived cartographic products for very large areas can be authenticated by appropriate statistical sampling procedures. Absolute accuracy within this plan deals with the level of thematic and positional correctness of a map defined in cartographic and statistical terms as of the date the map was made; while current representational accuracy deals with the statistical aspects of thematic accuracy as of any date a map is used.

In an area complementary to those discussed above, researchers have been experimenting with land cover mapping employing the Advanced Very High Resolution Radiometer (AVHRR) on the NOAA series satellites. At a format of four kilometer cells, this sensor's imagery has recently been employed to produce a level 1 "land cover" mosaic of the entire continent of Africa. Research, however, is needed concerning the most appropriate methods for verifying the accuracy of such products, and on the ability to use information

derived from such products in the modeling of fundamental biophysical and geochemical processes. In addition, considerable work is required to determine the potential of combining surface, aircraft, Landsat Thematic Mapper (TM), MSS, and AVHRR data into a multistage sampling frame to more accurately and efficiently create such continental scale map products (Figure 11). Another major issue is the very large spatial data base problems inherent in this type of activity. Such data bases are essential if we are to be able to employ the data generated in such studies as a basis for future monitoring and modeling as we attempt to improve our level of knowledge of those complex interactions which effect global habitability.

Classification of surface features, discussed in detail below, is fundamental to the study of global habitability. The ability to effectively employ remotely sensed data to improve the accuracy of our knowledge of the spatial distribution and temporal dynamics of surface features is essential. Such knowledge will enhance modeling efforts in many areas of the Global Habitability Program. Classifications of vegetation have been attempted for centuries, yet no general universal approach has emerged. Frequently, past criteria for defining vegetation classes have been vague, intuitive, overlapping, and confused. The choice of approach, in the past, has depended on the particular objectives of the classification, on its scale of application, and on the experiences, biases, and interests of the researchers involved.

An improved understanding of existing vegetation cover and those environmental factors which combine and interact to maximize or minimize the productive potential of given cover types is an important goal of this program. Different actual natural or potential vegetation types can have very different direct and indirect effects on biogeochemistry and energy exchange. Actual vegetation is the state of vegetation as it currently exists, and is a consequence of human actions, biological interactions, and the current status and changing state of the physical environment. Natural vegetation is defined herein as the state of vegetation that would exist without human disturbance, but with variation due to weather and biological factors. Potential vegetation is that vegetation which would exist in a general locale given: (1) a species list; (2) a fixed soil type and conditions; and (3) a constant climate, derived by calculating a time-average from a short (approximately ten year) weather record.

If we are to truly understand the biosphere, then we must improve the ability to derive information concerning these classes of vegetation through inventory, monitoring, and modeling on a global scale using remote sensing and appropriate sampling techniques and methodologies. Methods and criteria for establishing vegetation classes and for assigning map boundaries are seldom stated explicitly. Much reliance has been placed on intuition and first-hand experience. In fact, Rowe (1972) stated that for the forest regions of Canada, <u>only after vegetation classes were sketched out were the criteria to define them selected.</u> This practice is probably common and has been justified as being the only effective classification scheme available for regions as large as Canada. Inventories of such vegetation characteristics as biomass and productivity are essential in studies of biospheric processes such as the global carbon cycle. For these purposes, the actual vegetation of an area or

region must be recorded. Another reason for producing vegetation inventories and monitoring vegetation change through time is the prediction of vegetation potential -- the maximum biomass or productivity that could be sustained on a given site under present climatic conditions and soil conditions. Potential may be thought of as a form of capability; however, as typically employed, "potential" vegetation is the vegetation that would exist in the long-term under current conditions free from human influences of all kinds, and with infrequent natural disturbance.

For the study of the biosphere, a hierarchical classification scheme which employes each type, potential, natural and actual, vegetation information must be developed. Each of these three types can and indeed must be addressed at different spatial and temporal scales. The spatial scale determines the meaningful resolution of vegetation-type possible which, in turn, determines the types of information most useful in classification. On the global scale (10(8) Km (2)), 5-50 vegetation classes or formations are usually recognized and mapped. Physiognomy, which is the structure or appearance of vegetation, is a most common vegetation characteristic for classification (Beard, 1978), especially on a global scale. Climate, soils and geographical location are also used as criteria in the vegetation classification.

The UNESCO 1973 world vegetation classification is an example of a comprehensive, multifactor scheme. Physiognomic, climatic, geographic, and taxonomic factors were combined to produce over 50 vegetation classes. As deLaubenfels (1975) points out, classification such as the UNESCO scheme is not really vegetation classification, but is an examination of the types and distributions of world ecosystems. On a regional scale 10(4) to 10(7) Km, physiognomy and climate are commonly used as a basis for vegetation classification, while physiography is often taken into account in setting geographical boundaries. Taxonomic information becomes important at this spatial scale. Frequently, the type of vegetation is defined by the few dominant species, as for the boreal spruce-fir-white birch forest. The Map of Potential Natural Vegetation of California (Kuchler, 1977), is an example of regional classifications which have been developed that use all three criteria: taxonomic, physiognomic, and physiographic information.

Classification at local scales (1 to 10(4) Km (2)) have depended more heavily on taxonomic information, especially on the species composition of different communities. At this scale, numerical classification techniques have become practical, as has been demonstrated by analysis of the vegetation of California and Hawaii employing Landsat data. It is significant to note that use of computers for numerical classification of vegetation employing a variety of input data in the process frees the researcher from the necessity of mapping to a single predetermined classification scheme. Using existing technologies, the research is capable of quickly assessing classifications based on a variety of input data types before choosing those most appropriate to the issue at hand.

Even as imperfect and imprecise as our present classifications are, it is just such vegetation classifications and relationships between vegetation and environment which have been used to estimate the primary productivity of the world. For example, Rodin et al. (1975), used 106 vegetation formations,

classified from physiognomic, climate, soils, and physiographic information. An overall estimate of global productivity was then derived from estimates of the areal extent and average productivity of each class. Average productivity estimates (kg/yr) have been based on very few samples.

Lieth (1975), and Kieth and Box (1972), used a different approach in the estimation of global productivity. These researchers derived a computer map of worldwide evapotranspiration based on Geiger (1965), and established an equation relating net primary productivity to evapotranspiration using data from 52 field studies. From this information, they produced a map of potential productivity predicted from evapotranspiration (see Figure 9).

While potential vegetation never actually exists, it does provide a baseline estimate of what would be the expected state of the vegetation under a constant environment. It also has the advantage that it can be calculated readily and can be coupled directly to temporal and spatial models. The environment, especially climate and soils, has undeniable influences on vegetation. Moreover, environmental factors can be used as variables for predicting the potential vegetation of a site. This is the approach taken through applying the Life Zone Ecology System (Holdridge, et al., 1971) which has been applied to produce Life Zone Ecology Maps for 13 Latin American countries, Nigeria, Thailand, and the eastern part of the United States. The predictions can be compared to actual and natural vegetation to understand past changes and future trends.

It is generally accepted that there is an intimate interrelationship between environmental factors and terrestrial vegetation, to the point that knowledge of a given environment allows one to develop models which can predict certain expected characteristics of vegetation. At present, researchers rely on temperature, precipitation, solar illumination, and soil information to set general bounds on biomass and productivity, and to provide some basis for the predictive modeling of major vegetation characteristics for a given area. For example, a location with annual rainfall of 100 centimeters, a temperature regime typical of latitude 40 degrees, and a fertile soil can, left in an undisturbed condition, be expected to exhibit a closed canopy forest. Rainfall less than 20 centimeters per year below 60 degrees latitude results in a desert. If a list of species which occupy an area is known, predictions may improve, and remote sensing can assist in these studies. An example is seen in the works of Strahler, Estes and others in the Klamath, El Dorado, and Los Padres forests of California. In these areas, site scientific literature has been employed along with data on elevation, slope angle, and slope aspect to generate species site preference information for hardwood, coniferous, and chaparral vegetation. This data is then employed to generate a species site preference model of the area which is, in turn, used to verify unsupervised Landsat classification outputs. Conversely, if we begin from the other end of a causal connection, observations of the species present in an area, if made in sufficient detail, can provide considerable information about climate and soils. Additional work is required in this area to test the limits of these relationships, and to refine the accuracy of our estimates of actual vegetation and our models of potential vegetation and related information (i.e., biomass and net primary productivity).

Prior to the advent of satellite remote sensing, sufficient data on vegetation patterns that would allow objective and uniform classifications at regional, biome, continental or global scale for many areas of the Earth have been essentially impossible to obtain. Data, however obtained, are complicated by the enormous small-scale variability in vegetation. As a result, numerical approaches to classification have been applied only on local scales and at irregular time intervals, and typically employ loose classifications based on an approximate list of major species commonly found together. Moreover, even with the application of sophisticated statistical methods, many ecologists and biogeographers feel that non-numerical techniques have given more satisfactory classifications of vegetation.

In summary, a concerted research effort is required to design a set of land cover classification schemes which can be derived from remotely sensed data and used as input for global habitability studies. These should include specific standards defining the functional, spatial and temporal requirements for the spectral information to be derived, and the requirements of the platforms to produce the required levels of resolution. This effort must also include research designed to test the potential of remote sensing and ancillary data to provide information to scientists studying land capability at a variety of sites of important ecological significance.

II.5.3 RESEARCH AREAS

The preceding material provides the background for the development of a program of research to define the potential of remotely sensed and ancillary data to improve our understanding of the complex dynamic processes that affect habitability. Six research areas have been identified which are described in general terms below. Each encompasses a variety of high priority research tasks. The six major land surface study areas include research designed to improve and/or develop:

1. A global land surface inventory and monitoring capability. The focus of this activity will be on selected areas of critical scientific concern (this will include the initiation of research designed to increase our understanding of those factors which effect the capability of the land to support and sustain habitation).

2. Our ability to employ advance modeling approaches to land surface feature identification monitoring and prediction.

3. A set of land surface classification schemes for use with remotely sensed data which facilitate extraction of information for use in inventory, monitoring, and prediction of key parameters influencing global habitability.

4. Appropriate sampling strategies for combining and extrapolating detailed site-specific information gathered at the surface of the Earth to larger and larger areas (e.g., site ecosystem, biome, globe) through the use of aircraft and satellite remotely sensed data.

5. Processing algorithms and methodologies for extracting land surface information from remotely sensed data.

6. Techniques and methodologies for integrating and processing remote sensing data obtained from satellite and aircraft with data of many disparate types in a geo-referenced data base for integration, manipulation, storage, and retrieval by program scientists.

Specific examples of tasks in these research areas are as follows:

<u>Tasks for Research Area #1</u>: <u>Global Land Surface Inventory and Monitoring</u>

1. Develop a set of techniques and methodologies designed to employ remotely sensed and ancillary data to test and verify the strength of the relationships between surface cover types and critical environmental parameters.

2. Perform a first-generation global, land surface inventory to support all other science elements of the research program.

3. Investigate and determine selected areas of major scientific and social concerns, e.g., effects of deforestation/reforestation and desertification/desert reclamation, and establish baseline data needs to perform "selected area" surveys and monitoring.

4. Develop techniques for using Synthetic Aperture Radar data to characterize forest canopy structure and forest density.

5. Develop methods for use of synoptic resolution remote sensors to detect tropical forest cutting and regeneration, and higher resolution sensors (TM, aerial color infrared photography) to determine rate of cutting, erosional processes, and stages of regeneration.

6. Develop methods to improve measurement of shoreline length and density with remotely sensed data for assessment of changes in coastal regions and as input to productive capacity models.

7. Perform investigations with remotely sensed and surface-acquired data to determine snow area and location information.

8. Perform investigations of integrated ecosystems such as forests, grasslands, river basins, deserts, etc., using remote sensing and ancillary data in order to understand the interactions of land surface cover with life support processes.

9. Using remotely sensed data acquired in wavelengths from the visible to the microwave, determine the spectral difference between various surface soils and subsurface soils exposed by erosion, especially with respect to organic matter levels, iron oxide contents, soil moisture, and texture.

10. Collect and analyze thermal data acquired at various times throughout the day and night to determine if thermal inertia measures can be used as a basis for separation between land cover types.

11. Perform new generation global surveys, as required, based on new data standards and on changes in land surface components.

12. Conduct development activities to define and design improvements in analysis and sensor technology for inventory and monitoring.

<u>Tasks for Research Area #2</u>: <u>Modeling</u>

1. Collect and analyze remotely sensed and ground data from representative ecosystems (e.g., deserts, tropical forests) to determine normal variations within a year and from year to year.

2. Collect and analyze a time series of remotely sensed data acquired over various land cover types to determine vulnerability with respect to ecological zone, transportation systems, population growth, etc.

3. Develop the potential to employ time series of remotely sensed data in combination with data from other sources to predict changes in surface features.

4. Initiate research designed to produce a series of models for determining the capability of the land to support maximum productivity.

5. Develop surface cover dynamics models to provide inputs to hydrologic, biological, and other forms of process models.

6. Develop models which characterize natural vs. man-induced surface cover variation to predict actual and potential productivities.

7. Explore causal models that develop better predictive capability to estimate the impact of events on systems or areas of interest. Such models should address specific perturbations, whether the result of natural events or management practices, and focus on understanding the functioning of ecosystems.

8. Evaluation of models. Test models in a variety of geographic regions for:

A. Suitability of classification categories
B. Information provided by different sensors
C. Compatibility of classes derived from different sources of data
D. Effects of spatial precision and accuracy
E. Effects of registration
F. Accuracy of the models in describing spatial difference in land cover
G. Response to temporal variations
H. Costs of operating each model at different levels of detail

9. Develop and improve models that permit interpretation of remote observations in terms of vegetation and other surface feature characteristics for existing sensor systems. These models should provide for the input of other types of data to arrive at these interpretations.

Tasks for Research Area #3: Classification Systems

1. Develop and test, under a variety of environmental conditions, a set of remote sensing based land surface classification schemes within an ecological framework for the definition and delineation of ecological zones, and to assess variations within ecological zones.

2. Develop and test methods of obtaining, storing, and transmitting remotely sensed data useful for defining and delineating land surface units. Units should be uniform to some degree with respect to landform, topography, soil, vegetation, and climate.

3. Develop standards for mapping in terms of minimum mapping units, and the variability allowable within units.

4. Test the categories defined to assure the compatibility of remotely sensed classes with classes derived from other types of data, and to ensure that the system meets the needs of scientists.

5. Develop methods of obtaining, storing, and retrieving data and information at successive times to ensure that the classification set is suitable for multitemporal analysis.

Tasks for Research Area #4: Sampling

1. Analyze remotely sensed data acquired at various wavelengths and various spatial resolutions for different surface conditions for the purpose of improving the design of inventory and monitoring methods based on multistage sampling.

2. Develop a multistage, multisensor sampling strategy which uses remotely sensed and in situ data to estimate both the means and variance of land surface parameters, and which unifies the concepts of mapping and inventory in such a way as to minimize the error in both map and statistical information.

3. Investigate the needs of other program elements (e.g., energy balance) for mapping resolution, precision, and accuracy required.

4. Develop a multistage, multisensor strategy which optimizes the detection and localization of land surface change using satellite remote sensing data.

5. Develop and accomplish methods to assess the accuracy of inventory estimates and maps that can be obtained with multistage sampling strategies when little or no in situ ground data is available.

6. Develop methods, such as stratification, to use available information on topography, soils, geology, geomorphology, and climate to reduce the need for in situ ground data in inaccessible areas.

7. Accomplish stratification of global or selected land areas to support development of global or regional data bases.

Tasks for Research Area #5: Algorithm Development

1. Define the land surface information requirements/needs. These requirements will be used to define data requirements and the interfaces between remotely sensed data and other data. Information requirements will reflect both initial or baseline conditions as well as changes over time.

2. Develop appropriate preprocessing techniques to insure that the remotely sensed data resides in the data base in the correct format, and that it can be interfaced with other related data (e.g., climate, soils, etc.).

3. Establish appropriate research data base(s). Based on established requirements, acquire the remotely sensed data and input it to the data base.

4. Develop analytical techniques to derive information on spatial/contextual features. The techniques must be objective, repeatable, and extendable over geographic areas of interest.

Tasks for Research Area #6: Geo-based Information Systems

1. Investigate and recommend the appropriate data structure, data base capacity, and data base performance characteristics based on anticipated and surveyed needs of program scientists.

2. Determine the effects of positional accuracy on estimates derived from multiple data planes. Investigations will include: (1) the sensitivity of models to misregistration of data planes to each other (relative misregistration), and (2) the sensitivity of models to misregistration of the data set with respect to the surface of Earth (absolute misregistration or rectification).

3. Develop improved algorithms to enter registered data sets into the geo-referenced data base.

4. Participate in the design of the Global Land Habitability Pilot Research Information System, with emphasis on the provisions for inputting, storing, retrieving, and manipulating remotely sensed and ancillary land surface information in an efficient and user-friendly environment.

II.5.4 OBSERVATION REQUIREMENTS

In general, it will be necessary to employ two or more sensors operating in the spectral range from .38 to 14 microns, and in the microwave region. Data in the visible region is needed for soil/vegetation differentiation, forest type differentiation, and for separation of healthy from stressed or dying vegetation. Data in the near and middle infrared is needed for biomass determination, forest density classification, and the differentiation of dryland forest from wetland forest. Thermal data will be useful for differentiation based on temperature differences such as caused by

evapotranspiration, and for detection of stressed vegetation. Active microwave data is needed primarily in view of persistent cloud cover in the humid tropics for the detection of forest alterations. Research is also needed on the merging and analysis of both active and passive microwave data with visible IR data to increase land cover (especially forest) classification accuracy, for snowpack measurements, and for soil and canopy characteristics.

As stated previously, an ideal mix of sensors (viz., with respect to their spectral and spatial characteristics) fits closely with the concept of multistage sampling (see Figure 7). Initially, a multistage sampling design may require some combination of data from the NOAA-7 AVHRR, Landsat MSS, or Landsat TM in the first one or two stages. If additional research indicates finer resolution data for an additional stage is required, such data could be provided with aircraft until a spaceborne, pointable sensor with spatial resolution from 5 to 20 meters (depending on the results of additional research) is available. However, due to the persistent cloud cover in humid tropical areas, it is likely that an active microwave system will be essential to the monitoring of tropical deforestation. Such a system could be provided with a multifrequency (X, L, and/or C band), dual polarization, Synthetic Aperture Radar system capable of incidence angles from 35 to 55 degrees, and two look directions. Considerable research is still needed to develop the specific procedures for acquiring and analyzing microwave data and using it in a multistage design. This research can begin with Seasat SAR, Shuttle SAR, and aircraft-acquired SAR data. It would be desirable to combine data from a SAR system and a visible IR system in order to increase the accuracy with which the tropical forest can be monitored. Furthermore, it is desirable that such data be available at least on a quarterly basis. However, due to the cloud cover in humid, tropical areas, several orbiting sensors would be desirable to provide sufficient cloud-free data.

Generally, visible-infrared sensors should be in polar, sun-synchronous orbits and acquire data during the time of the day with high sun angles. More research is needed to determine the optimum times for the acquisition of thermal data, but it is anticipated that both daytime and nighttime acquisition will be required.

III. SUPPORTING SCIENCE ISSUES IN MEASUREMENTS AND INFORMATION EXTRACTION

III.1 INTRODUCTION

Land-related global habitability science issues call for the extraction of information from measurements to acquire new knowledge, expand existing knowledge, build models, and test models. The variety and complexity of Earth's land surface and its life forms guarantee that this will be a formidable task in its own right with its own issues. The ability exists today to make far more measurements locally or remotely than can be assimilated by a finite community of scientists. Therefore, careful consideration of information needs and extraction methodologies should precede and be the basis of each measurement experiment design.

The preceding chapter in this document shows that the information needs are many, the information types varied. Information extraction methodologies will range from direct use of local measurements as delivered, to chains of inferences based on remotely sensed radiance patterns. The measurement variables required to support global habitability research are extremely diverse. Putting aside the spatial and temporal measurement aspects and concentrating on measurement needs at one place at one time, there are quantitative and qualitative variables that are taxonomic, geometric, physical, geological, chemical, biological, and broadly descriptive in character.

Taxonomy of a site includes such items as plant species identification, soil types identification, geographic descriptors (river name, nearby town name), and general land cover description (farmland, prairie, forest). These variables range from fuzzy to exact, often call for human judgment to measure, and are usually readily measured by knowledgeable humans. The information so gathered may often provide first avenues into an information system when coupled with spatial information

Geometric variables include such items as where the plants are located on a site, the arrangement of branches and trunks or stems, the number and slope distribution of leaves on a plant, land slope, stream flow-direction, root depths, layout of human-built structures, tree crown height, soil roughness, and snow depth. While some of these variables are readily measured, others pose challenges not yet met. Leaf area index (LAI) is a geometric variable that can be very difficult to measure directly and non-destructively, as is leaf slope distribution. These are often inferred from radiance measurements. However, scene radiation modeling and analysis requires these parameters as independent inputs to avoid the circular reasoning that radiance measurements of LAI and slope distribution can be used as inputs to model radiances of leaf distributions.

Physical variables include such items as the optical scattering properties of plant and soil constituents, aerosol and hydrosol size, distribution, density, and optical properties, weights of biomass, plant and soil moisture, evapotranspiration flux, stream and river flow velocity profiles, humidity,

temperature, wind direction and velocity, rainfall rate, surface albedo, snow wetness, radiation budget and radiance field, soil constituent optical and transport properties, soil and plant thermal properties, and boundary layer transport properties. Here, too, the measurements range from the well-accepted (temperature, humidity, flow velocities) to the difficult and argumentative. For example, radiance measurement of a few percent absolute accuracy is very difficult to achieve in a laboratory setting, and is an active area of research today. The situation is compounded in difficulty in a field or a satellite measurement setting.

Geological variables include such items as land slope structure, fault locations and directions, stream, river and lake bed influences, soil constituent influences, glacial geometries, magnetic and gravitational anomalies, rock types and occurrences, strata orientation, and subsurface hydrology influences. Measurement of these variables generally requires the human knowledge base of a competent geologist supported by the local and remote sensing technologies common to mineral and petroleum exploration.

Chemical variables include soil inorganic and organic chemical constituents, local gas identities and densities, nutrient concentrations, trace element and compound concentrations, and associated reaction rates in both living and non-living components of the land surface. The dynamics of carbon, nitrogen, phosphorous, and sulfur are of particular importance. In situ measurement techniques are in an active state of development as pointed out in Section II.3.3. Laboratory capabilities include the full well-developed range of chemical analytical equipment and techniques. Field sample measurements in a laboratory setting are more likely than in situ measurements in this area.

Biological variables include the full range of biochemical concentrations and reaction rates, plant phenologies, soil microbiota activites and their interaction with plant cover, plant conversion rates of nutrients to biomass and effluents, decomposition rates and products of dead biomass, and net primary productivity. Most of these variables are difficult to measure, particularly in situ.

The broadly descriptive variables include such items as general plant well-being, soil quality, climate character, water availability, and appropriateness for various kinds of agriculture and animal husbandry. These are largely qualitative human judgment measurements. They are difficult to quantify but are key descriptors of the habitability of a place.

The variables to be measured tallied above are not exhaustive but simply descriptive of the magnitude of the measurement problem. Instruments and measurement techniques are available for some subset of the desired measurements. A large portion, however, require substantial development to achieve in situ measurement capability even at one place at one time. Those variables which might be inferred from remote sensing radiance measurements are only loosely coupled to detailed physical, chemical, and biological variables. The definitive coupling models are in the early stages of active development today. This is an important aspect of the next topic: the spatial and temporal extents of the measurements problem.

Most of the variables involved in global habitability are distributed in space and vary in time. Current values are determined by space-time dynamic behavior, that is, transport phenomena. Fluxes and concentrations must be measured over such an extent and such frequency that both the spatial and temporal limitations imposed by sampling theories (Nyquist criteria or spline theory, for example) are satisfied for the measurement task at hand. In the preceding chapter there are implied tasks ranging from centimeters-seconds space-time scales to thousands of kilometers-decades scales. When there are significant variations on a scale of meters to tens of meters of a variable to be measured over tens of kilometers, in situ measurement networks become prohibitively complex and expensive.

The major hope for making measurements over the spatial extent implied in global habitability is remote sensing technology. However, as noted earlier, the coupling between remote sensing radiance measurements and the variables appropriate to global habitability is only partly understood at this time. Identification of crops with multispectral, multitemporal remote sensing data has been reasonably successful in LACIE and AgRISTARS, though not without developmental problems. Leaf area index, biomass, and net primary productivity estimation from remote sensing appears hopeful but is yet unproven over a wide range of plant life. Soil type identification over farmland has been reasonably successful, at least in defining relative differences and boundaries, though moisture confounds the measurement to some extent. Soil roughness, crusting, and moisture may be hopeful; moisture measurement by remote sensing has been pursued for over a decade, without strong success, but with the promise that microwave measurements will someday do the job. Of course, some of the global habitability variables of interest are most directly measured by remote sensing, such as upwelling radiance in energy budget work.

At this time, the most promising approach to global habitability information extraction from measurements appears to be combined in situ and remote sensing integrated field studies with very careful attention paid to sampling design. A balance must be struck between the manageability of the local in-depth study that fails to describe the totality and interactions of an ecosystem, and the shallowness of the global study that tries to measure a few variables everywhere. Study designs should begin with information sought and appropriate sampling strategies; these should drive the system design. That is, instrumentation, communication network, data acquisition, and information extraction system design should follow and serve the global habitability studies program.

III.2 SCIENCE ISSUES AND THEIR IMPORTANCE

The general importance of science issues in land-related global habitability measurements and information extraction was inferred in Chapter II. There is, simply, much that is not known about energy balance, hydrology, biogeochemical cycles, land biological productivity, and land cover on a global scale. Enhanced knowledge begins with measurements designed to yield information from data.

The principle science issues in this area are:

1. Some of the variables called for in land-related global habitability studies are difficult to measure at best in situ, either inherently or because of the complexity of the measurement apparatus and technique. These variables should be identified and one of three approaches taken:

A. Create better measurement capability at reasonable cost in money and time.

B. Infer these variables from others more easily measured, either in situ or remotely.

C. Change to different variables that carry similar information content.

2. With the exception of direct radiance measurements from active or passive sensors, remote sensing data analysts will need to infer variable values from radiances. This calls not only for continued scene radiation and atmospheric effects modeling and analysis, but also for more supporting ground truth measurements at local sites than has been common over the last decade.

3. To take advantage of the rapid areal measurement capacity inherent in remote sensing and the more detailed knowledge obtainable from intensive local site measurements in an integrated manner, it is essential to engage in careful sampling design before the measurements programs begin. The bane of field studies is collecting data that no one looks at, while failing to collect what people really needed in retrospect.

4. Information extraction techniques in land remote sensing have focused on cover type estimation. Not only will this area need to be enhanced, but spatial and temporal classification techniques need to be developed for the inference processes of biological, hydrological, and water, nutrient, and energy budget estimation. In addition, the in situ measurement system and associated communication network need to be integrated into the overall information extraction system as part of the available data base.

III.3 RESEARCH AREAS

Research areas that address the science issues in measurements and information in land-related global habitability are described below in four groups: in situ measurements, remote sensing measurements, sampling design, and information extraction.

In situ Measurements

1. An in situ sensor requirements study should be conducted to determine gaps in current technology of measurements of component, plant, and scene properties. Component properties include leaf angle distribution, leaf reflectance, leaf transpiration, leaf turgidity, soil composition, soil moisture, soil microbiota, groundwater, and non-leaf plant parts properties. Plant properties include energy, water, and nutrient budgets, leaf area index, biomass, and composition.

2. Based on the results of the in situ sensor study, key sensors should be designed, prototyped, tested, and described in scientific literature.

3. The spatial distribution of even the in situ sensors in large area field studies may be large. Therefore, it is reasonable to evaluate the utility of existing Data Collection Platforms with an eye to development of an automated in situ sensing network with communications capabilities.

Remote Sensing Measurements

1. Current aircraft and spacecraft sensors and missions should be evaluated for their utility and limitations in estimating land cover, biomass, leaf area index, nutrient status, evapotranspiration (energy budget) and water budget for vegetative canopies. The same should be done for estimating nutrient budget, composition, structure, infiltration and water storage characteristics, and energy balance of soils. These evaluations should be made in both temperate and tropical climates and over large watershed scale areas.

2. Laser sensors on aircraft platforms should be employed to investigate measurement of forest canopy height, biomass, leaf area index, primary productivity, and forest structure.

3. The largest research task is to establish the chains of inference from radiance measurements to global habitability variables estimation. This means developing, testing, and exercising scene radiation models to invert radiance measurements to biomass, leaf area index, vigor, evapotranspiration, and net primary productivity. Spectral and temporal measurements coupled with radiative transfer modeling show promise here. Both optical and microwave sensing is assumed over both cultivated and natural vegetation. Similar processes should be developed to infer soil type, roughness, crusting, soil moisture profile, soil hydraulic properties, organic matter and iron oxide content, and soil litter characteristics. Albedo measurements should be made and will be directly useful as climatological inputs.

Sampling Design

1. The first research task to be accomplished is the organization of existing data on crops, forests, soil, and water by region and climate into a well-designed data base.

2. The major research issue here is to establish a regional and stratified sampling strategy that will increase a global habitability knowledge base in an efficient manner. This involves target areas identification, target variables identification, strata construction, and sampling unit definition, as well as techniques for aggregation.

3. Once the sampling strategy is firmly established for things as they are, a change detection and forecast system should be built.

Information Extraction

1. Land cover identification is one of the most fundamental areas in information extraction research using remotely sensed data. This includes biome stratification (boundary delineation), ecotypical species distribution, and general cover type identification by either manual or machine processing. Detailed supportive research efforts are required to do this well in image registration and rectification, labeling methods, use of elevation data or information, data base construction, automated control point determination, dissimilar sensor data registration, and use of in situ sensory data in information extraction.

2. The land cover identification and supportive research efforts described above should be combined with the scene radiance modeling efforts to attack the most important information extraction research task: the estimation of biological variables from remote and local coordinated measurements. Biomass, leaf area index, net primary productivity, and the influencing environmental parameters of energy, nutrient, and water budget are the target variables.

IV. INFORMATION SYSTEMS SUPPORT

IV.1 INTRODUCTION

Throughout the preceding sections of this report, the basic science issues and the research needed to address them have shown a unique dependency upon information systems. All efforts discussed involve data collection, reduction, analysis, and presentation. Thus, it is appropriate that the multi-disciplinary information systems needs required to support the research described herein receive a focus comparable with the science programs themselves.

Three principal objectives guide our information systems planning:

1. From the viewpoint of both cost and value, the key asset is the basic data obtained from the environment. Thus, every effort will be made to maximize the accessibility of all forms of relevant data to the scientific community to foster scientific cooperation through the development of geocoded data bases and a network of distributed computers.

2. Many research centers in this field have already made substantial investments in information system facilities. Further, there is a strong dependency upon the particular programs and data structures unique to each installation. Every effort will be made to enhance the productivity of these facilities rather than to replace them.

3. The science and technology of information systems is progressing at an accelerating pace. This is especially true in the data base management, artificial intelligence, and networking areas required by land global habitability research. Mechanisms must be developed and firmly set in place to continuously incorporate these advances throughout the duration of the research program.

Information Systems Support addresses comprehensive computational support for the five major research areas discussed in the body of this report. Included is the implementation of a network to provide participants with shared facilities for the exchange of data; the development of a data base management system, including provision for data directories and catalogs; and development of a geographic information system for the processing and analysis of multilayered, multisource data sets referenced to the same coordinate system. Initial development work on information system and networking requirements will be coordinated with the NASA Information Systems Program.

IV.2 PRINCIPLES OF SCIENTIFIC DATA MANAGEMENT

Based on the experience of the past two decades of space activities, a number of principles that are fundamental to the successful management of scientific data can be stated as the required basis of a Land Global Habitability Information System.

1. There should be active involvement of scientists from inception to

completion in order to assure production of, and access to, high quality data sets. Scientists should be involved in planning, acquisition, processing, and archiving of data.

2. Oversight of data management activities should be implemented through a Land Global Habitability Science Steering Committee.

3. Data should be made available to scientists in a manner suited to scientific research needs and have the following characteristics:

A. The data formats should strike a proper balance between flexibility and the economies of nonchanging record structure. They should be designed for ease of use by the scientist. The ability to compare diverse data sets in compatible forms may be vital to a successful research effort.

B. Appropriate ancillary data should be made available, as needed, with the primary data.

C. Data should be processed and made available to scientists in a timely fashion.

D. Scientists will be made aware of what data are available through accurate catalogs.

E. Proper documentation should accompany all data base entries that have been validated and are made available.

4. A proper balance between cost and scientific productivity should govern the data processing and storage capabilities provided to the scientist.

5. Special emphasis should be devoted to the acquisition and production of structured, transportable, and adequately documented software.

6. Scientific data should be suitably annotated and stored in a permanent and retrievable form. Data should be purged only in accordance with procedures established by a Land Global Habitability Science Steering Committee.

7. Adequate financial resources should be set aside early to construct and maintain the information system, and these resources should be protected insofar as possible.

IV.3 CHARACTERISTICS OF THE RESEARCH INFORMATION SYSTEM

To pursue data-intense research programs, scientists need access to data, software, and hardware. They must understand how to exploit them effectively. Many participants in the Land Global Habitability Program are expected to have their own data processing capabilities, data, software, and hardware. This section describes the key elements of the information system under consideration. Material concerning data sources, networking requirements, systems environment, systems capabilities and some thoughts on implementation of the system are presented below.

Sources

The highly variable structure of research data sets requires a system to accommodate many data types from a variety of sources. Of particular importance is the need of the system to respond to new data types and formats. Inherent in research is a continuing evolution of data products as the research itself identifies the need for improved data. Examples of large volume sources of data expected to feed into the system include:

DOC: Landsat, Metsat, GOES, and other imaging sensors on a variety of platforms as well as oceanographic and atmospheric observations, and also meteorological, climatological, and other types of surface data including census data.

NASA: Aircraft and Orbiter active and passive sensor data, experimental sensor data, and historical data.

USDA: Soils, forest and agricultural data.

DMA/DOD: Cartographic products in analog and digital form.

USDI: Cartographic products, again in analog and digital form such as geological, geophysical, and land-use/land-cover data.

Data sets will be integrated into the information network at the highest possible level practical.

Network

Land Global Habitability investigations will involve a dispersed set of users, many of whom are working on individual component projects supporting one or more of the major research areas. Many investigators will have the need to share common data sets. Means must be developed to make the existence of useful data sets known to interested researchers if expensive duplication of effort and abandonment of tasks for lack of data are to be avoided. Mechanisms must be developed to transfer data sets from one participating institution to another. Through a network of computers between participating NASA centers and institutions, ready access should be provided to data bases of general interest and comprehensive on-line directories pointing users to various network nodes where such data bases reside. Network users should also have access to algorithms and processing capabilities at other institutions.

Environment

The system envisioned herein should be capable of operation in two modes. In one mode the environment would be as user-friendly as possible. (In the standard mode, however, a more elaborate interface would provide access to the full functionality of the system.) It is not intended that the typical research user should require a detailed understanding of the system. After a short indoctrination in protocols, basic capabilities, etc., researchers

should be able to operate competently throughout the system from a remote location.

Capabilities

The system should provide access to a number of general purpose science packages such as a scientific subroutine library, a statistical analysis package, a graphics subroutine library, a test formatting package, and image analysis and classification routines. A small technical staff including programmers would be available for service, training, and consulting. Training packages and documentation would be available on the standard software. A library will be created of supporting documentation and bibliography on issues relevant to the data stored (e.g., instrument operation, data collection procedures, processing algorithms, data set validation procedures, user results). A bibliographic information service would also be available in support of the library.

Implementation

Each of the major participants in global habitability research has, in the course of previous research activities, developed a core staff with skills in computer science disciplines. For example, one organization may be strong in image processing, while another may have strengths in networking, or geographic information systems. It is important to identify the contribution each of the participants can make, and develop specific implementation assignments to properly exploit such potential contributions.

An important design principle for the overall information system should be that data archives should be physically located in those institutions which have the maximum expertise with the particular data sets. Institutions already possessing a computing system compatible with the Land Habitability Network and with the need to manage significant local data bases will probably prefer to be a computer node on the Land Global Habitability Network. Comprehensive network and data systems standards must be developed covering important aspects of the Network. Strict adherence to the various standards by all participants will be essential.

A goal for the Land Global Habitability network work is to eventually become integrated into a wider scope, multidisciplinary Global Resources Information System. This will allow access to other science information systems (oceanographic and atmospheric) to facilitate multidisciplinary Global Habitability research.

IV.4 SCIENCE STEERING COMMITTEE

Oversight of research information system activities should be accomplished by a Land Global Habitability Science Steering Committee. Members of this Steering Committee would represent research community needs by reviewing, critiquing and recommending hardware, software, procedure definition, implementations, and alterations. This group should also assist in defining the division of responsibility between research projects and data management organizations for data acquisition, preprocessing, storage and distribution.

An important activity of the Steering Committee will be to identify and select data sets that should be incorporated into the system, to evaluate their usefulness in their present state, and to define those steps that must be taken to prepare those data sets in a form that will provide maximum utility.

IV.5 RESEARCH INFORMATION SYSTEMS TASKS

Information Systems tasks can be divided into the following major areas:

1. Networking
2. Data management
3. Development of standardized data sets and directories
4. Geo-based information system

IV.5.1 NETWORKING

Once the types of prospective participants (e.g., ecologists, hydrologists, geologists, geographers, computer scientists, physicists, electrical engineers, etc.) in the Land Global Habitability program are known, a survey should be conducted and published containing an outline of the range of existing hardware, software, data, and data collection capabilities of the institutions which could be involved in the program. This will serve as baseline for the implementation of the network. The primary function of the network would be to facilitate access to, and processing of, science data. The principle justification for such a network is the creation of a capability which no individual institution could maintain.

Near-Term Considerations

In the near-term, planning for a land pilot data system should be initiated as soon as practical. Such a pilot system can serve as a testbed for the evaluation of networking and data management concepts and technologies. As these concepts and technologies are refined, a final pilot network may be installed. User requirements could also be analyzed and evaluated in more detail and lead to the design work on an operational system. Many commercial network services are emerging which allow the interconnection of dissimilar systems. Work should be initiated to survey and assess the full range of potential offered by these services. At present, compatibility between the computing equipment of participating institutions is the principle impediment to rapid establishment of a network.

In the longer term we should be aware that a major trend in computing is toward a 32-bit personal work station. With appropriate graphics and software support, these appear to be superior to time-sharing systems for certain elements of the scientific data processing envisioned in the bulk of this document. These systems should be seriously considered for incorporation into the overall system as they become available. The potential of low-cost satellite communications networks should also be examined.

IV.5.2 DATA MANAGEMENT

Information management requirements for the Land Global Habitability

Information System should be characterized as early as possible in the planning process so that processing and data needs can be met within the constraints of the research task schedules. A number of data base management systems have been developed and made commercially available over the past decade. These systems typically support one-to-many and many-to-many relationships within data, and are excellent tools for locating specific data records that are less than, greater than, or equal to a number of user-supplied criteria. While these may be useful for constructing data directories, they lack the special functions of proximity operators and are not particularly efficient nor effective at storing and searching raster/image data. Graphics or imaging capabilities are not readily available in these systems. Analysis of the capabilities of commercial data base management systems will have to be made in order to evaluate the degree to which they are able to fill some needs of the Land Global Habitability system.

Geographic information systems have been developed which employ schemes to store data in multidimensional planes (usually polygonal or raster) in a fashion which allows rapid entry, display, manipulation and analysis of geographically registered data sets. These systems typically lack advanced facilities for locating and displaying point or textual data based on complex, nongeographic search criteria. The two data selection criteria of major concern in Land Global Habitability studies are expected to be place and time. Therefore, a primary information management thrust under the Land Global Habitability Program must be to develop a geographically referenced data management system (GIS) with the kind of nongeographic, logical operators generally available in relational data base management systems.

One item of immediate concern is how and to what extent data may be managed across the network of participants in the Land Global Habitability Program. Frequently, the time and costs associated with preparation of data in standard formats can be an inhibiting factor to critical scientific research. A prime example of this is the time and cost of registration of ground-observed measurements to remotely sensed data; yet, adequate accuracy assessment is rarely achieved without it.

IV.5.3 DEVELOPMENT OF STANDARDIZED DATA SETS AND DIRECTORIES

Data structure is a function of the kinds of data collected. Classical data types include raster (cell), vector, polygon, transect, point, and three-dimensional. Data management architectures developed to support Land Global Habitability research must be flexible and capable of accepting all data types. Techniques will be required to interrelate these data structures. Data interchange format development should be a joint scientist/data processing professional effort. Formats should be reviewable by a Science Advisory Committee and distributed to all participating institutions.

Each of the individual supporting institutions will bring with it an approach to data management. Usually these approaches were developed to support the on-going research needs of that organization. In all likelihood there is some compatibility between the various approaches, but each will doubtless have its peculiar operating and access characteristics. The potential of a data base

management system is closely aligned with the development and maturity of the data processing network.

As previously discussed, relational data base systems (which could provide a flexible base for the Information Management Directories) are now becoming available along with most hardware product lines. Such systems should be evaluated. Relational data base systems are typically structured for commercial applications with short records and simple data structures. However, the requirements of computer-assisted design and manufacturing systems are rapidly enhancing these systems to handle the long and complex structures of the type generally associated with geographic data. Geo-referenced relational systems are planned to be installed as soon as stable packages are available.

Data cost will represent a significant portion of the overall investment in Land Global Habitability studies. Requirements are generally for correlative data sets over the same test site. Currently, such data sets are frequently archived in a variety of storage media and formats, compelling the user to sort all records to determine the desired data subset. An automatic cataloging system would convert relevant information about these disparate data sets into a structured system. These data sets could then be queried on the basis of a number of keys, especially location, time, and sensor.

These catalogs will provide Land Global Habitability with an efficient mechanism for selecting the required data to support experiment design and subsequent analysis. Once catalogs have been constructed at participating institutions, a high level Data Directory describing the data holding of each participant would be constructed. This directory would contain information pertaining to the various data archives in such a fashion that it could be interrogated for pointers into proper catalogs. Sharing of such information between projects and/or research centers could potentially eliminate duplication of expensive preprocessing of the same data by providing a proper level of visibility.

IV.5.4 GEOGRAPHIC INFORMATION SYSTEM

The geographic information system is that portion of the data base which provides investigators coordinate-referenced data sets. The initial steps in developing a GIS will be to assemble data sets identified by participating scientists. Tools for the integration of multiple data sets must be made available to selected test sites. These data sets may then be registered to each other and also to a geographic coordinate system as appropriate. Subsequently, proposed models could be exercised utilizing from selected areas and data planes within the integrated data sets.

Integration of data sets with different formats (e.g., line, polygon or image raster) will require improvement in data entry and handling to ensure data capture. Other issues such as nesting of remotely sensed image data at different resolutions, while maintaining data integrity, will also require investigation. Techniques for combining the geographic information system within the framework of the computational network that has been established

will be studied. Ultimately, it should be an achievable goal for each node on the network to access the full GIS capability.

Finally, development of a prototype Global Data Base which includes a Geographic Information Capability is more than simply a "scaling-up" from a similar system which has been developed for less extensive geographic areas. Many areas of research and technology development will have to be addressed. Research on new data structures, formats, access, and query among others should be examined as should artifical intelligence means for improving efficient man-machine interaction. The storage and retrieval of the massive amounts of data required to maintain a Global System will require development of more efficient search and file storage techniques.

In conclusion, the information system discussed herein should be developed as rapidly as possible if research computational needs of the Land Global Habitability Research Program are to be adequately coordinated. As such, it is imperative that an Information Systems Working Group reporting to the Land Global Habitability Science Steering Committee be established. This group should convene as rapidly as possible to develop a plan that addresses in detail the key research and program operational needs such as networking, directories, and geo-based information systems.

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16. Abstract

The scientific investigation of the viewpoint of the biosphere that living organisms and their physical and chemical environment are bound, inseparable parts of one set of closely coupled global processes of the global "biogeochemical" system -- life and life support -- cycles -- is discussed as one of the major scientific challenges of the next decade by building from understanding land processes to interdisciplinary, holistic studies of biospheric dynamics including human impacts.

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